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Gas Cooling and Dehumidification

page 26

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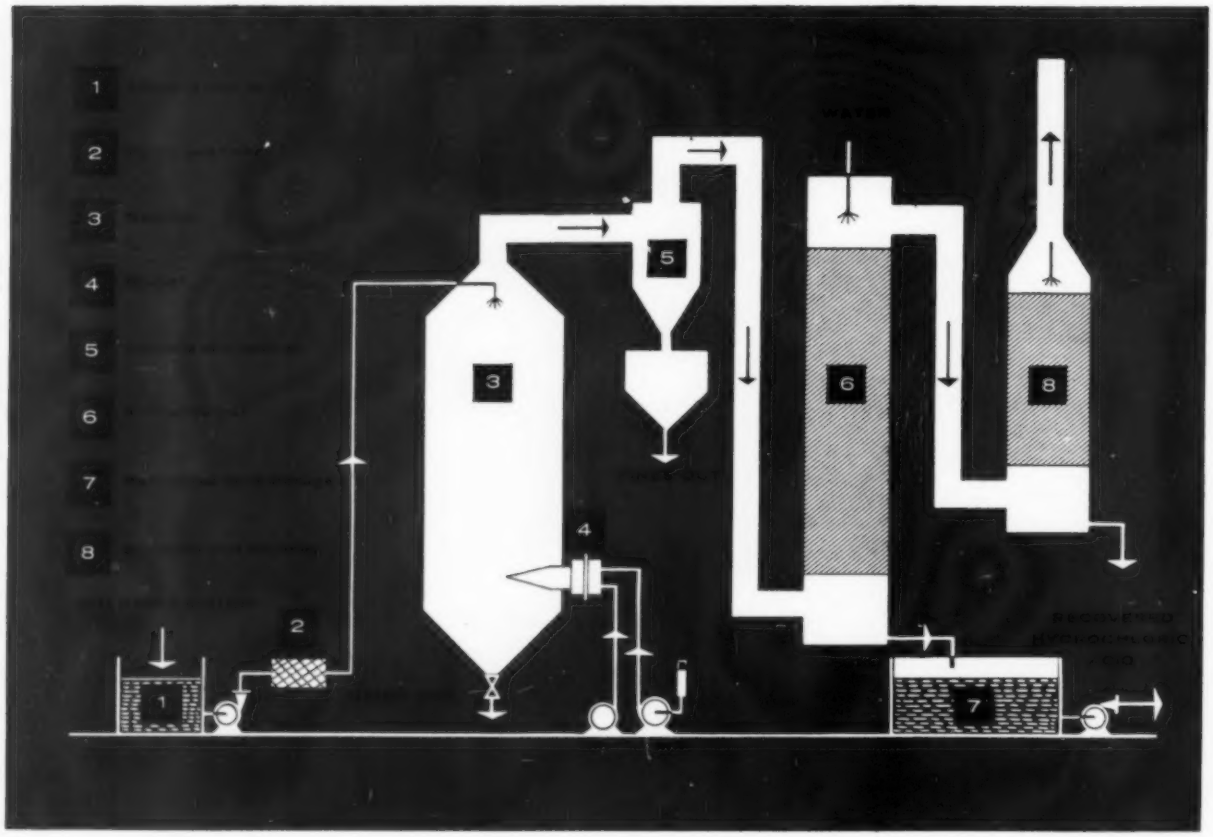

the AMAN process hydrolyses chlorides to HCl and oxides

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DIGEST OF INDUSTRIAL AND TECHNICAL DEVELOPMENTS

Chemonuclear Reactor Design Study

BEFORE the commercial exploitation of ionising radiation for accelerating chemical processes becomes a practical proposition, complete investigations under industrial conditions in a chemonuclear reactor will be essential to resolve many unknown factors. Preliminary studies undertaken by Atomics International* on a chemonuclear reactor suitable for such pilot studies suggest that a 1 Mwt dual-flow organic liquid cooled reactor, based on a modification of the Piqua organic moderated reactor, offers promise. It is estimated that about 3.4%, or 34 kW, of the total radiation would be available in the chemical process stream. In the basic chemonuclear reactor design, (which would need modification to suit particular chemical reactions), the chemical process stream to be irradiated flows downward, after preheating to approximately the temperature of the reactor coolant, through the centre tube and around the outer tube of each fuel cell. The chemical does not contact the fuel cladding. The organic liquid coolent—diphenyl or a mixture of polyphenyls—is circulated through the reactor through a separate piping system and is cooled in a steam generator.

The total cost of radiation, at 0.9 capacity, for the projected chemonuclear reactor is estimated as follows:

Fixed charges	0.52	dollars	per	kWh
Fuel cost	0.10	,,	,,	,,
Operating and maintenance	0.29	,,	,,	,,
Total:	0.91	,,	,,	,,
Process steam credit	0.05	,,	,,	,,
	0.86	,,	,,	,,

This is appreciably lower than the costs for electron accelerator machines, Co-60, and Cs-137 sources of approximately the same power (30 kW) reported in recent radiation application surveys (1.49-1.59, 1.90-2.63 and 2.15-3.58 dollars per kWh respectively).

Typical reactions suggested for possible study are the polymerisation of ethylene, the reaction of benzene and water to form phenol, and the irradiation of methanol to produce ethylene glycol.

* Chemical Engineering Progress, October, 1960, p.72.

Shock Waves Aid Chemical Research 7,000 m p h Heating Process

THE shock tube technique which by means of shock waves travelling at speeds up to 7000 miles an hour, will heat gas molecules to thousands of degrees in millionths of a second, is a technique which has been used by scientists at the Shell Laboratories, Emeryville, to answer a number of important questions concerning very rapid gas reactions at high temperature and pressure.

One problem is that mixing, heating and cooling, tend to obscure the true results of a chemical reaction performed in conventional apparatus; thus, when a gas A reacts with another gas B a small amount of gas C and a large amount of gas D may be formed. The quantities of C may be so minute that the conclusion might be drawn that the result of the reaction is the formation of D, when what may have happened is that in the relatively long time required to heat these materials to say 5000 degrees centigrade, and then cool them, a large amount of D is formed—even though C may be the major product at 5000 degrees. The answer is to make the heating and cooling times as close to nothing as possible.

The shock tube used by Shell is a two-compartment 18-ft length of 6-in. steel pipe with one end connected to a 3 ft diam steel vacuum chamber and the other, the higher pressure section, is closed, the two being separated by an aluminium disc. The high pressure section is filled with a light, inert gas, preferably helium, and another aluminium disc subdivides this section into two, one for the reaction section of the tube which contains the gases under study.

To start the reaction, the disc separating the high pressure chamber from the reaction chamber is ruptured by an electric discharge, thereby causing a shock wave to travel through the gases in the reaction chamber. As a result, gas molecules in the wave path are raised thousands of degrees in temperature within an interval of time of the order of a few millionths of a second.

A second discharge, electronically triggered at a predetermined time by the first one, breaks the disc at the vacuum chamber. The light or driver gas is evacuated and the reaction products are cooled very rapidly and left in much their condition at the maximum temperature, ready for chemical analysis.

The successful design and fabrication of the metal discs were engineering feats because the discs must rupture in exactly the same way for each operation. In order to ensure that this happens each disc has embossed on it a circle divided into six equal parts, the depth of the embossing determining when it will rupture.

The Electric Arc for Chemical Syntheses

TO this same field of high-temperature high-pressure reactions belongs the electric arc heater which, in its latest form, is capable of producing temperatures in the region of 12,500°C and pressures of 15,000 psi over sustained periods and without the disadvantage of product contamination which has attended previous efforts of this kind.

The latest development not only offers a new route to the fixation of nitrogen but it also holds promise of wide application in the processing of petrochemicals. A prototype designed by the Westinghouse Electric Corporation has been operated at a power input of 1700 kW but a ceiling power input of 30,000 kW is being planned. With the prototype temperatures as high as 5700° C have been reached and maintained and a gas velocity of 3400 mph has been attained; velocities ten times greater than the

speed of sound are expected when the gases are expanded through a hypersonic exhaust nozzle.

An outstanding feature of the performance is the low level of contamination which is in sharp distinction with other arc devices which, through consumption of electrodes and the walls of the containing chamber, have led to a level of contamination amounting to as much as 10 per cent of the mass of gas flowing through the apparatus. The Westinghouse unit provides a contamination level not in excess of 0.2 per cent although this is not considered to be the limit of its performance in this respect.

The success of the new machine is attributed to the design of the two electrodes which form the terminals for the arc. Each consists of a hollow doughnut-shaped ring placed horizontally, one directly above the other, with water pumped through the hollow rings for cooling.

The arc is started by drawing it across the gap between the two rings, and is then rotated around the gap at high speed.

Arc rotation is accomplished by a magnetic field set up by d-c coils arranged around the outside of the heat chamber, which with water-cooling, conserves the electrodes, and, indeed, repeated tests have left the electrodes undamaged, indicating a lack of contamination from this source.

The working fluid, such as air or nitrogen, enters the arc chamber and passes into the arc through openings near a water-cooled copper heat shield. This water-cooled heat shield, which can withstand arc temperatures well above 10,000°F. without eroding, protects the walls of the arc chamber. After leaving the arc, the fluid passes through a water-cooled nozzle.

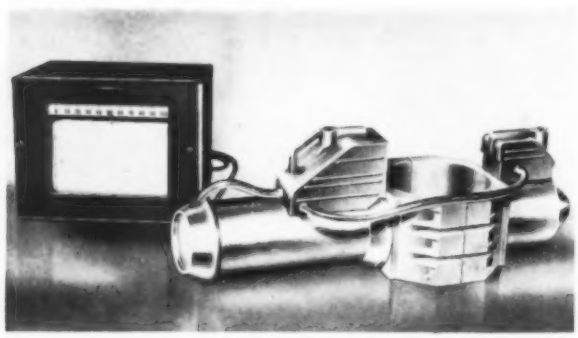
Designed to accommodate a 1.2 lb/sec flow of either air or nitrogen, the prototype arc heater can supply gas at 1500 lb psi with a constant enthalpy of more than 2000 Btu/lb for as long as 10 minutes without damage or measureable gas contamination, with a 50 per cent plus efficiency of heat transfer to the gas. So far, the highest pressure at which tests have been conducted is 730 lb psi. Other tests with a power input of 549 volts and 5046 amps (9450 kW/lb/sec) have raised the enthalpy air passing through the chamber to 4670 Btu/lb.

Westinghouse expect within the next two years to have a full scale version of the prototype available.

Continuous Measurement of Liquid Density using a Radioactivity Gauge

DENSITY changes in liquids, solids and slurries may be measured and recorded without any contact with the material under inspection. This method has been developed by Saunders-Roe & Nuclear Enterprises Ltd. who recently demonstrated their Density Gauge type 336 (illustrated).

Basically the system consists of a Caesium 137 source "looking through" the inspection volume (normally a pipe of between 4 in. to 10 in. diameter) at a plastic phosphor mounted on a photomultiplier. The amount of radiation which reaches the detector is dependent on the density of the material in the process.



"Stopping power" of this system is of the order of 30 times greater than that of an ionisation chamber and hence with similar sources the sensitivity is much better.

The photomultiplier is arranged to give a signal which is monitored by a recorder. This is arranged to have a suppressed zero, so that the required variations in density are covered by the recorder scale.

A complete automatic standardisation system is incorporated. The measuring source is "switched off" and a calibrating source "switched on" for one min at 10 min intervals. This calibration source, which is mounted in a known and constant relationship to the scintillation counter, produces a fixed dose rate at the counter which automatically compensates for decay in the measuring source.

The signal produced by this dose rate is then fed into the recorder and the overall Wheatstone bridge sensitivity (i.e. both zero suppression and span) adjusted automatically so that this dose rate corresponds to a fixed position on the scale and the span represents a fixed fraction of the dose rate.

Overall calibration of the system is in terms of a standard dose rate and is independent of E.H.T. and temperature variation. In the standard model the interval between calibrations is 10 min, the time of calibration 1 min and the response time 10 sec.

Many uses for such gauges in the Chemical Industry are immediately apparent and it will be interesting to see if they prove to be cheaper than existing equipment.

Separating Volatile Liquid Mixtures by Continuous Gas-Liquid Chromatography

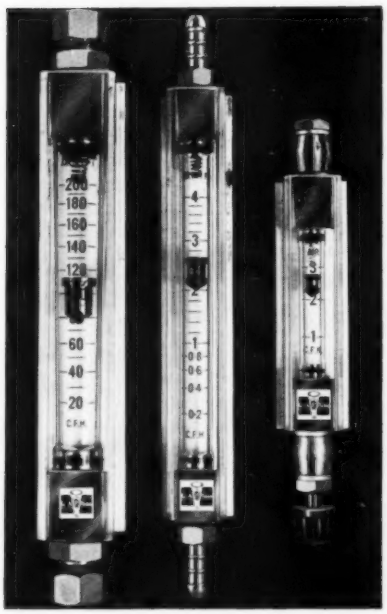
A NEW process for the separation of "difficult" volatile liquid mixtures has been successfully applied on an experimental scale by P. E. BARKER and D. CRITCHER* of the Department of Chemical Engineering, University of Birmingham. Fundamentally an extractive distillation process, they describe it as a countercurrent analogue of gas-liquid chromatography. In principle, a solid containing an absorbed solvent is allowed to flow down a column countercurrently to a stream of gas, the liquid mixture to be separated being injected continuously at the midpoint of the column. The method depends on the components distributing themselves differently between the two phases. Thus one component is carried upward in the gas stream and the other downward absorbed in the non volatile liquid.

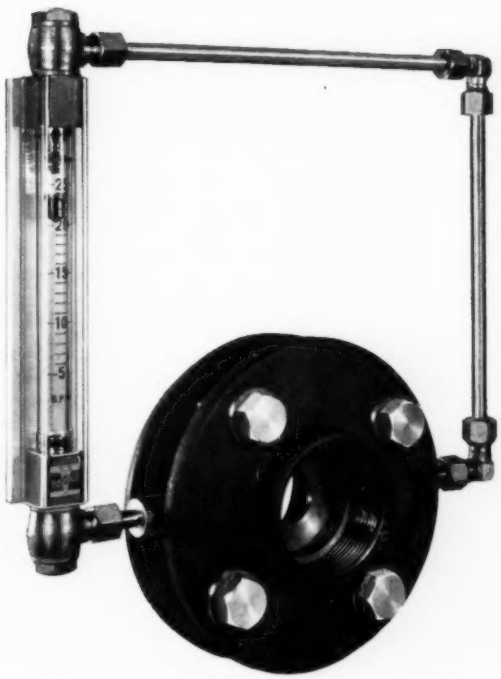
For the purpose of proving the method, a mixture of benzene (b.p. 80.1°C) and cyclohexane (b.p. 80.7°C) has been successfully separated at a rate of 30 cm^3/hr in a 1 in. diameter column 4 ft long. In this column the non-volatile solvent, polyoxyethylene 400 di-ricinoleate, absorbed on 10/20 mesh kieselguhr, was arranged to flow at a controllable rate countercurrently to a stream of slightly pressurised dried and preheated air. The more strongly absorbed component carried down in the liquid phase was removed from the column by an excess of air in a stripping section below the rectification column. The less strongly absorbed component was carried upwards in the airstream. Both streams were passed through cold traps to condense out the separated products. Complete separation was achieved over a wide range of operating conditions.

* Chemical Engineering Science, October 1960, p.82.

GAPMETER DEVELOPMENT

SMALL GAPMETERS LARGE GAPMETERS SHUNT GAPMETERS





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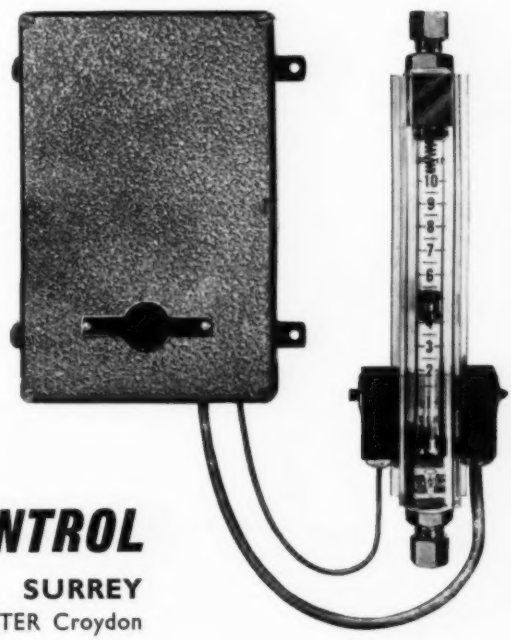
The Gapmeter is a direct-reading variable-area flowmeter for liquids and gases. The well-known combination of vertical tapered tube and friction-free indicating float is used but the criteria of small size, low price and safety are given major importance. The designs use the minimum possible number of components, all completely interchangeable and all made from bar stock. Clear, steady flow readings are provided having a degree of accuracy adequate for all but the most stringent test work.

The immediate success of the Small Gapmeters, (pipe sizes $\frac{1}{8}$ in., $\frac{1}{4}$ in. and $\frac{3}{8}$ in.), has led to the development — still retaining the original design criteria — of the Large Gapmeter series for pipe sizes $\frac{1}{2}$ in., $\frac{3}{4}$ in. and 1 in.

In the Large Gapmeter, the tapered metering tube is of metal or resin-glass laminate. The float has an extension with an indicating button visible in the sight tube below.

For pipes larger than 1 in. the Gapmeter design criteria can only be maintained by measuring an accurate fraction of the main flow. The Shunt Gapmeter uses an orifice plate to shunt less than 1 per cent. of the main flow through a Small Gapmeter in a by pass line.

THE FLO-SCAN



The Flo-scan is a flow operated alarm switch designed for use with Gapmeters. A small lamp housing and a photo transistor are located on opposite sides of the Gapmeter glass tube, and the alarm is operated when the indicator float or button of the Gapmeter interrupts the light beam: this ensures failure to safety.
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Regeneration of Pickle Liquor

SULPHURIC acid regeneration from spent pickle liquor at a cost of under 19 dollars a ton on a 100% basis—taking no account of credit for recovered iron oxide—is made possible by a new vacuum process developed by Singmaster and Breyer of New York. If credit for recovered iron oxide is allowed, this cost would reduce to less than 15 dollars a ton. Comparative costs for other processes are 29 dollars a ton for the spray-evaporator process and 33.20 dollars a ton for the Ruthner sulphate-chloride process.

The Singmaster and Breyer process comprises essentially three steps: (1) concentration of pickle liquor and the resultant crystallisation of ferrous sulphate monohydrate in a multiple-effect evaporator; (2) roasting of ferrous sulphate monohydrate in a multi-hearth furnace under conditions such that substantially no SO_3 is generated; and (3) generation of 98% sulphuric acid in a contact acid plant. Advantages claimed for the process are as follows. Fumes are automatically absorbed by the steam jet which is used to generate vacuum. The process operating temperature is low, and therefore relatively inexpensive materials can be used for the plant. Thermal economy is enhanced by utilising the heat of dilution of 98% sulphuric acid in the second evaporator. The use of an evaporative crystalliser ensures proper crystal size and shape, readily filterable and washable. By adding small quantities of sulphur-bearing material during roasting, the combination of pickling plant and regeneration plant is completely self contained as regards acid requirements.

Sulphur Special issue 1960, p.16.

Control of Single-Effect Evaporators

ALTHOUGH the dynamic characteristics of distillation column reboilers have been treated in the literature, until last month the similar topic of the unsteady behaviour of a vacuum evaporator was apparently a totally neglected topic. The investigation referred to*, centered around the control of a single-effect, internal-calandria (1520 sq ft surface) natural-circulation evaporator, and consisted of three parts, theoretical and experimental studies of its control characteristics and an analogue computer analysis of alternative control systems suggested during the course of the first two parts of the work. In the first part, from heat and mass balances, equations are obtained which show that pan level depends upon product density and that the response of the product flow depends both on product density and on pan level.

In the experimental work an evaporating pan, equipped with one principle and three subsidiary control loops, had the former (for regulating feed flow according to concentration as determined from b.p.r.) disconnected and instead connected to a sine-wave generator.

The work carried out with this set-up showed that the theory giving the response of pan level and of product density and flow, to disturbances in steam flow and in feed flow density and temperature, gave results which were in fair agreement with those observed experimentally.

The analogue study of alternative control systems shows that, in systems with a density-control loop, of which the main arrangements are,

(I) Level-control by regulation of product flow, and control by regulation of (a) feed flow, or (b) steam flow, and

(II) Level-control by regulation of feed flow, and density-control by regulation of (a) product flow, or (b) steam flow,

with the exception of (IIb) which was not tested, all give satisfactory control but (IIa) gives a faster product density and flow response than sytems (I), but exhibits interaction which the other systems do not.

* "The control of a single-effect concentrating evaporator, J. A. Andersen, LWA Glarson, F. P. Lees. Paper read to Soc. Inst. Tech. London, Nov. 17."

Siemens Gas-producer

ON January 22, a century ago, that versatile inventor SIR WILLIAM SIEMENS patented his regenerative gas furnace, a sequel to his introduction of the regenerative principle in which the combustion gases from solid fuel impinged on "an extended surface of brickwork, the bricks in one wall being opposite to openings in the other, thus forming what is called open Flemish bond." Siemens was to become perpetuated in the "Siemens-Martin" open-hearth steel furnace after the MARTIN brothers in France had been granted a licence to include the regenerative principle at their Sireuil works. Yet on this centenary emphasis should be laid on the fact that the regenerative gas-furnace was invaluable apart from metallurgical industries. The inventor foresaw the use of heating gases for chemical works, the gases being cleansed to avoid contamination by sulphur as happened when using solid fuels.

From his experience in working his "Flemish bond" regenerative furnaces Siemens went on to his gas-producer, and to his specifying "the pre-heating of gaseous fuel prior to its entering into combustion." He showed how inferior fuels and poor quality gas could be used with advantage when gases were pre-heated. So successful were his demonstrations that one manufacturer on seeing a Siemens furnace working maintained that some surreptitious heating was being used as addition, for it seemed hardly possible that such relatively small amounts of fuel could attain such high temperatures. The manufacturer waited throughout one night hoping to see the fraud exposed. While FREDERICK SIEMENS, brother to KARL WILHELM or WILLIAM, used a first experimental gas furnace at the well-known Siemens-Halske works in Berlin, it was in British works that the regenerative gas-furnace came to large-scale application from 1861. One was tried at the Birmingham flint-glass works of Lloyd and Summerfield, a second at Mexborough, while at the Chance and Hunt works in Smethwick came the final proof with FARADAY describing

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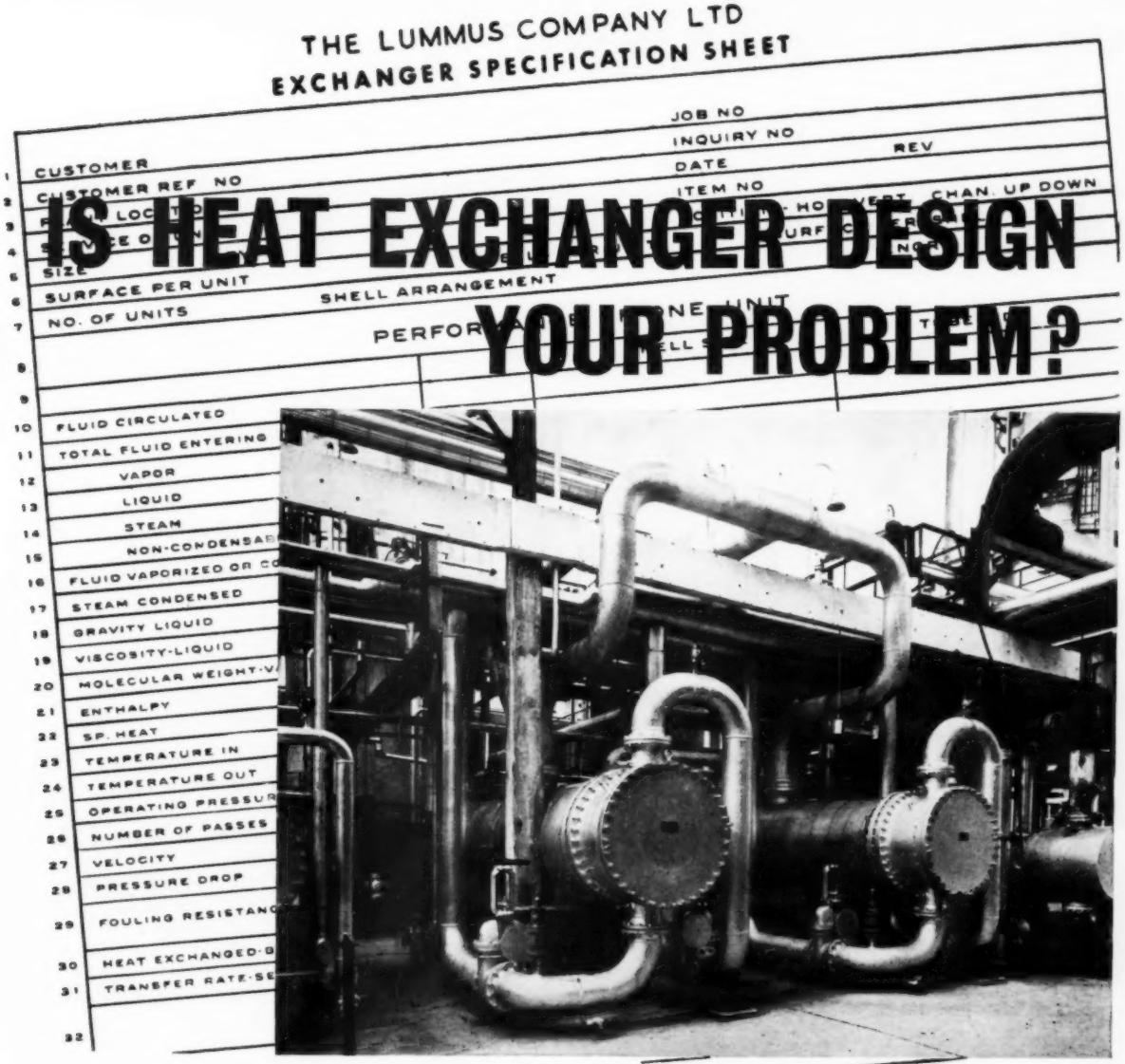

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his study of this example in his last lecture to the Royal Institution. Further demonstration of the Siemens gas-producer came with an award at the International Exhibition in 1862, with a further award for the "Siemens Four a Gaz a Chaleur Regénérée" at a Paris exhibition, and with a paper on the invention read before the British Association in 1865. Though in the "*Phil. Trans.*" of 1798 the Admiralty chemist JAMES SADLER had suggested a furnace using pre-heated air for combustion, only when Siemens put pre-heating into practice along with his regenerative brickwork and producer-gas did theory become applied on a large scale.

Boundary Layer Theory Applied to Air Dryer Design

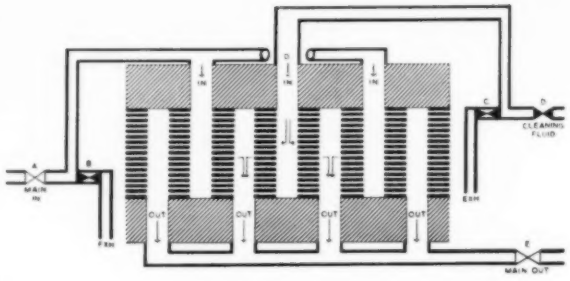
FOR drying continuous web-material, an air dryer has been developed recently in America which, it is claimed by the designer, MR. T. A. GARDNER of Pulp and Paper Engineering, Marathon (a division of the American Can Company), has two to three times the drying capacity of a conventional air dryer. It has the additional advantage that the jet force acting on the web is considerably less, and therefore high drying rates can be achieved without disastrous effects on the web surface.

The conventional air dryer, in which air is supplied at a high velocity parallel to the surface, invariably operates at high Reynolds numbers where the boundary layer is mainly turbulent, and theory suggests that heat transfer may be expected to increase with the 0.8 power of the velocity. Drying rates are thus limited by operating power costs—since fan horsepower increases approximately as the square of the velocity—and by the possibility of surface damage if air velocity is increased unduly.

The Gardner dryer, on the other hand, is designed to operate at low Reynolds number with a thin laminar boundary layer, under which conditions the heat transfer coefficient is proportional to the square root of air velocity divided by continuum length. A typical Gardner dryer has a series of nozzles directing air normal to the web surface and extending over the width of the web, spaced at $\frac{1}{4}$ in. to 1 in. centres and mounted $\frac{1}{8}$ in. to $\frac{1}{2}$ in. above the surface. The nozzle orifice is less than 0.025 in. Air velocity at the orifice is 10,000-20,000 ft/min. Since the volume of air from the very narrow orifices is small, power required is not excessive and the kinetic energy of the jets is low. The characteristic length of the continuum is half the distance between jets. The resulting flow on the surface approximates to that of a theoretical flat plate but deviates from pure theory in such a way as to augment heat transfer. The theoretical heat transfer coefficient is about 40 Btu/ft² hr. deg F, whereas in practice it is believed that a figure of about 55 Btu/ft² hr. deg F is achieved.

Precise Separation of Solids

IN these days of perpetual innovation few types of equipment can be expected to hold an unchallenged position in a particular field over an extended period. In the field of filtration, for example, sintered metal and ceramic plates and cartridges which have held an important place for many years now have to meet competition from newer types of clarifying equipment, one of the most recent being a multi-rod system wherein the clearance between bars provides the filtering space. The rods are ranged in disc-like circular layers, each layer having 12 straining edges. Compared with a gauze strainer of the same size units constructed in this way have a free area which is six times greater than that of the gauze unit and compared with sintered metal filters the free area is also much greater. Mechanically this new design is exceptionally robust and can be constructed in any of the usual materials of construction. For this reason it is suitable for the straining of liquid metals such as liquid sodium in high-temperature heat-transfer circuits. The nature of the design also provides a close control over the size of particle separated which it allows to pass through. The minimum size of particle retained is approximately 2 microns.



The accompanying diagram shows an arrangement of filters of this type for continuous operation. The liquid to be treated is fed at the point "Main End" so that sediment is retained at the surface of the "IN" channels. When the resistance to flow becomes excessive valves A and E are closed and valves D and B opened. The cleaning fluid then discharges the solids through point B. Dirt introduced into the system from valve D is also retained at the surfaces of the "IN" channels for D from where it may be removed by opening valves A and C.

Inert Gas Ion Pumping

ALTHOUGH practical use is made of the phenomenon of gas pumping at the walls of discharge tubes in many electronic devices and in ultra-high-vacuum systems, little is yet known of the processes by which gas molecules are held in the glass. To throw some light on the mechanism of the process, G. CARTER and J. H. LECK* of Liverpool University have recently investigated the sorption of inert gases at the glass walls of an ion pump, devoting their observations particularly to the release of the sorbed gas rather than the previous sorption.

The glass bulb of either a Bayard-Alpert ionisation gauge or a simple tube of diode construction, with an open grid type of electron collector and an axial filament, was used as the test surface. The glass was bombarded with positive ions having energies ranging up to 1000 eV. All the gas taken up during the bombardment was subsequently removed by baking up to 350°C.

The investigators found that (a) the sorbed gas could be recovered from the glass, section by section, by localising the heating with a fine gas flame; (b) there was no take-up of gas when there was no discharge, even with the filament hot; (c) when the walls acquired a positive potential both the rate of gas take-up and the maximum quantity sorbed are reduced very considerably; (d) the sorption depends critically on the energy of the ions striking the walls. These observations were all consistent with a mechanism where gas molecules are held just under the glass surface, and desorb by what is effectively a single activated jump. The desorption energy was found to be spread through the range 20 — 50 K.cal/mole — values not inconsistent with the few available measurements of the diffusion of inert gases through glass.

* A.V.S. October 1960, Liverpool University.

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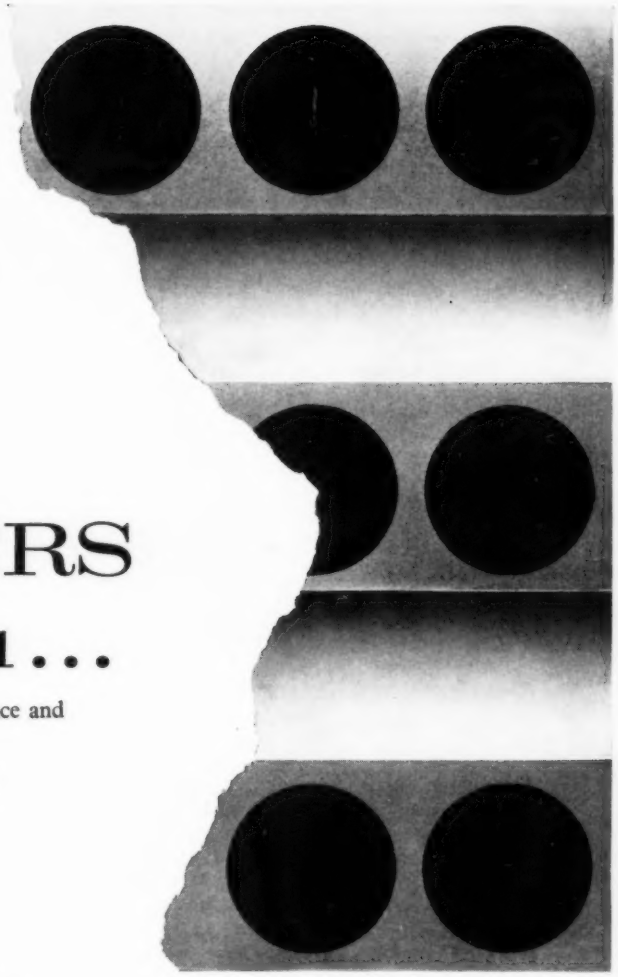

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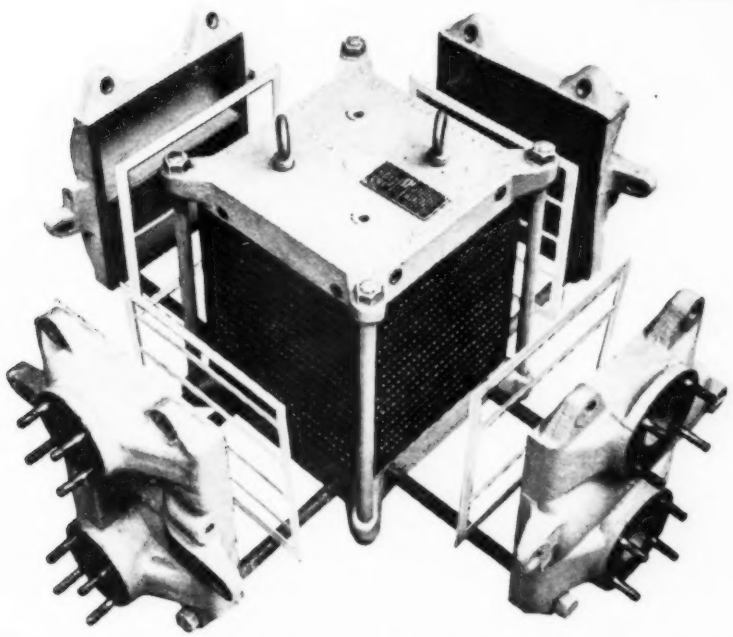

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Preliminary Announcement

THE Department of Chemical Engineering will accept undergraduate students from 1961-62 session onwards. The course will last for four years and lead to the Honours Degree of Bachelor of Science.

Admission. Candidates must be qualified for Matriculation in accordance with the regulations summarized in the pamphlet Information for Applicants, and will be required to have passed the General Certificate of Education or an equivalent examination at Advanced Level in Chemistry, Physics, and Pure-and-applied Mathematics (or Pure Mathematics and Applied Mathematics). There will be no Intermediate Examination course.

Full particulars of the syllabus will appear in the Prospectus of the Faculty of Applied Science for 1961-62. Lady Trent Professor: R. EDGEWORTH JOHNSTONE, B.Sc. Tech. (Manc.), D.Sc. (London) M.I. Chem. E., F.R.I.C.

Aluminium Chloride for Heat Transfer?

BECAUSE gaseous aluminium chloride exists as a monomer $AlCl_3$ at high temperatures and as a dimer Al_2Cl_6 at low temperatures, it may have interesting possibilities as a heat transfer medium and as a working fluid for gas turbines. At temperatures at which there is an appreciable fraction of both monomer and polymer, the effective specific heat and thermal conductivity are considerably enhanced as a result of the association equilibrium conditions. As a thermodynamic working cycle fluid, because of the relatively large difference in the gas constant between the monomer and dimer, the ratio of turbine work to compressor work will be greater than for a gas that does not dissociate; and the energy losses will have relatively small effect on the overall efficiency.

To obtain data for making engineering calculations of thermodynamic cycles employing aluminium chloride vapour, a theoretical evaluation of the basic physical properties and thermodynamic constants of aluminium chloride has been carried out for the U.S.A.E.C. at the Oak Ridge National Laboratory*, over a temperature range 500°-1200°K. The investigators (M. BLANDER, L. G. EPEL, A. P. FRAAS, R. F. NEWTON) also considered possible corrosion problems, and concluded that aluminium chloride vapour could be satisfactorily contained with high-nickel-content alloys.

They also considered certain typical engineering applications—the use of gaseous aluminium chloride as an intermediate heat transfer medium in a molten-salt-fuelled reactor, a gas turbine cycle operating an aluminium chloride, and a binary vapour cycle employing water vapour. In none of these examples did they find any outstanding advantages over more conventional media. Nevertheless, they conclude that the estimated values of thermal conductivity, heat capacity and viscosity indicate that aluminium chloride may be a unique gaseous heat exchange medium requiring very low pumping power, and that it may well prove to have some outstanding advantages in systems where these unique characteristics can be exploited to the full.

* Report ORNL-2677 Reactors-Power TID-4500. Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.

Tube Plates for High Pressure Heat Exchangers

NEW theoretical and experimental data for design of high pressure heat exchangers are presented by D. E. HARTLEY* in a paper advocating the use of thin tube plates for this type of plant. His analysis is based on the stiffening effect of tubes on tube plates; it takes note of, but differs from, that of MILLER which is the basis of the design procedure in British Standard Specification 1500: 1958. MILLER considers the plate as a continuous disc, weakened by the tube holes and strengthened by the tubes. HARTLEY considers the tube sheet simulated by a series of concentric annular beams supported rigidly at their edges by the tubes. On this basis it is found that when the tube plates are thin bending is restricted to a narrow outer zone of the plate, and this has been confirmed experimentally. The question of ligament efficiency does not arise and it is possible to see the significance of the main parameters. Also the precise tube arrangement at the outer edge of the plate can be taken into account.

In a heat exchanger having two tube plates, the latter are subject to surface pressures, loads in the tubes and a peripheral load due to the pressure in the header; there is also a load from the shell due to its change in length relative to the tube nest, caused

* *Nuclear Engineering*, Dec. 1960, p. 557.

DIARY

Institution of Chemical Engineers

January 10. *North Western Branch.* Chemical Engineering Lecture Theatre, The Manchester College of Science and Technology, Jackson Street Manchester. "Selection of prime movers in the petroleum chemical industry" by H. H. MEYER (Associate Member). **6.30 p.m.**

January 18. *North Western Branch.* Lecture Theatre A, The Houldsworth School of Applied Science, Reservoir Street, Leeds, 2. "Chemical process design," by J. M. COULSON (Member). **6.30 p.m.**

January 24. The Geological Society. Burlington House, London, W.1. "Lecture on mass transfer in drops and bubbles," by F. H. GARNER (Member). **5.30 p.m.**

January 24. *North Western Branch.* Birkenhead Technical College. "Experimentation and reactor design in process research and development," by W. WADDINGTON and W. D. BETTS. **7.30 p.m.**

Institution of Mechanical Engineers

January 18-19. Symposium on Pressure Vessel Research Towards Better Design.

January 25. Ordinary Meeting: Thomas Lowe Gray Lecture. "The Early Development of the Dracone Flexible Barge," by PROFESSOR W. R. HAWTHORNE.

Institute of Refrigeration

February 2. "A New Conception in Cooling Tower Design," by CARL MUNTERS and LENNART LINDQVIST.

Institution of Engineering Designers

February 2. Lecture. "Some Aspects of the History of Engineering Drawing Leading to Drawing Standardization," by P. J. BOOKER, A.M.I.E.D.

Annual Exhibition of the Institute of Physics and The Physical Society—1961

January 16-20. 10 a.m. to 1 p.m. The Horticultural Halls, Westminster, London.

THE PERKIN CENTENARY TRUST

Awards For The Academic Year 1961-62

MAUVEINE, the first important synthetic dye, was discovered by WILLIAM HENRY PERKIN in 1856. This discovery marked the birth of the dyestuffs industry and of the greater part of the organic chemical industry of the world. The centenary of this historic event was commemorated in 1956 by Celebrations that were widely supported by many organisations having an interest in chemistry. The Perkin Centenary Trust was established as a lasting memorial of this occasion, and to promote technical education in all aspects of the manufacture and application of colouring matters.

Applications for the following awards should be made on forms available from the Secretary, and must be received not later than May 1st, 1961 : —

The Perkin Centenary Fellowship

This award is offered for one or two years for the purpose of higher study of any subject approved by the Trustees. Candidates will be required to show *either* that they have had experience in an industrial firm or other institution concerned in the manufacture or the application of colouring matters, *or* that their intended field of study has a direct bearing on these subjects. The value of the Fellowship is £750 per annum with an additional grant of up to £100 per annum towards certain designated expenses. It may be tenable, from October 1961, at any university, technical college or other institution approved by the Trustees.

The Perkin Scholarship

Two such awards are offered, each for two years, renewable at the discretion of the Trustees for one further year, to enable candidates employed in an industrial firm or other institution concerned with the manufacture or the application of colouring matters to receive an education at a university or technical college. Each award will have a value of £350 per annum. This may be increased, at the discretion of the Trustees, to £400 per annum if the candidate appointed is required to live away from his normal place of residence. There is no means test and a successful candidate is not debarred from receiving the whole or a part of his normal salary from his employers during his tenure of the Scholarship.

Perkin Travel Grants

Applications are invited from teachers concerned with the study of any aspect of the manufacture or the application of colouring matters at a university, technical college, or other institution. The purpose is primarily to assist those for whom grants are not readily available from other sources. Each application will be considered on its merits. The Trustees, however, expect that preference will be given to applications from lecturers, senior lecturers and readers, or the equivalent grades in other institutions, wishing to gain experience at a similar institution or in industry overseas. The object of the intended visit must be clearly stated (e.g., study of special techniques, apparatus, or industrial processes: to assist in some stated research project ; or to study some specific educational method) and the applicant will be expected to devote sufficient of his time to that object so that effective study is possible. Grants will be available towards the cost of travel and maintenance for periods, related to the purpose of the visit, of from one to three months.

Enquiries relating to the above awards should be addressed to The Secretary, The Perkin Centenary Trust c/o The Chemical Society, Burlington House, London, W.1.

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CHEMICAL ENGINEERS

Required by the Chemicals Division of B.O.C. Ltd. Applicants should have an honours degree in chemical engineering or corporate membership of the Institute of Chemical Engineers, plus at least 3 years' industrial experience and should preferably be between the age of 25/30 years.

The vacancies exist in Works Research at the North Ireland and North-Eastern Factories. Applicants should have an interest and aptitude for process investigation, plant design and cost study.

The positions are progressive and there is a contributory pension scheme.

Apply in writing to:
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Cleveland Row, St. James's, S.W.1.

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The main responsibilities of the Chemical Engineers in I.S.R. Company's Technical Department include process control, product development and pilot plant operation, efficiency of materials usage and plant performance, and interesting design work on varied projects covering almost the entire field of chemical engineering unit operations.

The appointments offer valuable experience to graduates in a modern large scale continuous process and plant, with the added attraction of residing and working in the South Coast area of Hampshire's New Forest.

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Chemical Engineers, preferably with some post-graduate experience in industry, are invited to apply to the Personnel Manager of the Company at Hythe, near Southampton.

AUSTRALIA

THE UNIVERSITY OF NEW SOUTH WALES, SYDNEY

LECTURER IN CHEMICAL ENGINEERING

The University invites applications for appointment to the position of Lecturer in the School of Chemical Engineering, Kensington.
Salary: £A1759 range £A2464 p.a.
Commencing salary according to qualifications and experience.
Applicants should possess an honours degree in chemical engineering or be eligible for corporate membership of the Institution of Chemical Engineers or possess equivalent qualifications. Wide industrial experience is essential and some teaching experience would be an advantage though not essential.
The successful applicant will be required to lecture in all branches of chemical engineering, with special reference to chemical engineering thermodynamics and kinetics.
Subject to passing a medical examination, appointee will be eligible to contribute to the State Superannuation Fund.
Appointee will be eligible for 12 months study leave on full salary after six years' service.
First-class ship fares to Sydney of the appointee and his family will be paid.
Four copies of applications, including the names of two referees, should be lodged with the Agent General for New South Wales, 56, Strand, London, W.C.2, and a copy forwarded by airmail in an envelope marked "University Appointment" to the Bursar, The University of New South Wales, Box 1, Post Office, Kensington, New South Wales, Australia, before **13th January, 1961.**

CHEMICAL ENGINEER

RESEARCH

Anglo-Lautaro Nitrate Corporation, a large mining and chemical company with operations in the North of Chile, requires a graduate Chemical Engineer (M.Sc. or B.Sc.) for a position in its research organization.
The successful candidate will be expected to take charge of pilot plant operations, perform mathematical studies of processes and related problems associated with the production of sodium nitrate, potassium nitrate, iodine and boric acid.
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The Company's operations and research laboratory are located near Antofagasta, Chile. It maintains full supporting services including a mechanical design section and large machine shop facilities: Applications with full details of qualifications and experience, age and family status should be addressed to:

Mr. C. S. Hill,
Nitrate Corporation of Chile Ltd.,
Chile House,
20/24, Ropemaker Street,
London, E.C.2.

AUSTRALIA

The University of New South Wales
Newcastle University College
Vacancies for Academic Staff

The University invites applications for appointment to the following position at Newcastle University College:

Lecturer in Chemical Engineering.
Salary range: £A1759-£A2464 p.a.

Subject to passing a medical examination, appointee will be eligible to contribute to the State Superannuation Fund.
First-class ship fare to Sydney of appointee and his family will be paid.
Four copies of applications, including the names of two referees, should be lodged with the Agent General for New South Wales, 56 Strand, London, W.C.2, and a copy forwarded by airmail in an envelope marked "University Appointment" to the Bursar, The University of New South Wales, Box 1 Post Office, Kensington, New South Wales, Australia, before **13TH JANUARY, 1961.** Candidates outside the United Kingdom and Ireland need only submit one copy of their applications to the London address.

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Head of Department of Chemical Engineering

Applications are invited for the Headship of the Department of Chemical Engineering which is to be created in the near future.

The Department organises full-time courses for the Diploma in Technology, the B.Sc. (London) degree and qualifications of the Institution of Chemical Engineers. Research is being developed in collaboration with industry. Plans have been approved for a separate new building for Chemical Engineering which will provide excellent facilities for the extension of teaching and experimental work.

Applicants should be well qualified Chemical Engineers with responsible industrial experience, including that of original design. It would be useful to have previous teaching and/or research experience relevant to the development of under-graduate and post-graduate work in collaboration with industry.

The starting salary will accord with the qualifications and experience of the candidate and will be within the range of Grade V or Grade VI of the Burnham Report, i.e. between £2,100—£2,500 per annum.

The appointed Head will be permitted to undertake consultant work.

Further particulars and forms of application may be obtained from the Registrar, Bradford Institute of Technology, Bradford, 7.

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CHEMIST

required at Warren Spring Laboratory (D.S.I.R.), Stevenage, Herts., as Scientific Officer or Senior Scientific Officer, for work on chemical methods for extraction of metals from ores, involving both fundamental studies and problems arising from applied work on specific ores, e.g. use of complexing agents for liquid/liquid extraction of metals and studies of chloridising and chlorinating reaction mechanisms. Candidates should have a preference for fundamental research. Qualifications:—1st or 2nd Class Hons. degree in Chemistry. Some experience with chemistry of metal/organic compounds desirable. Age at least 26 for S.S.O. and at least 3 years' post-graduate experience required. Salary:—S.O. £690-£1,144. S.S.O. £1,250-£1,540. Forms from Ministry of Labour, Technical and Scientific Register (K), 26, King Street, London, S.W.1, quoting reference F.905/0A. Closing date 10 February, 1961.

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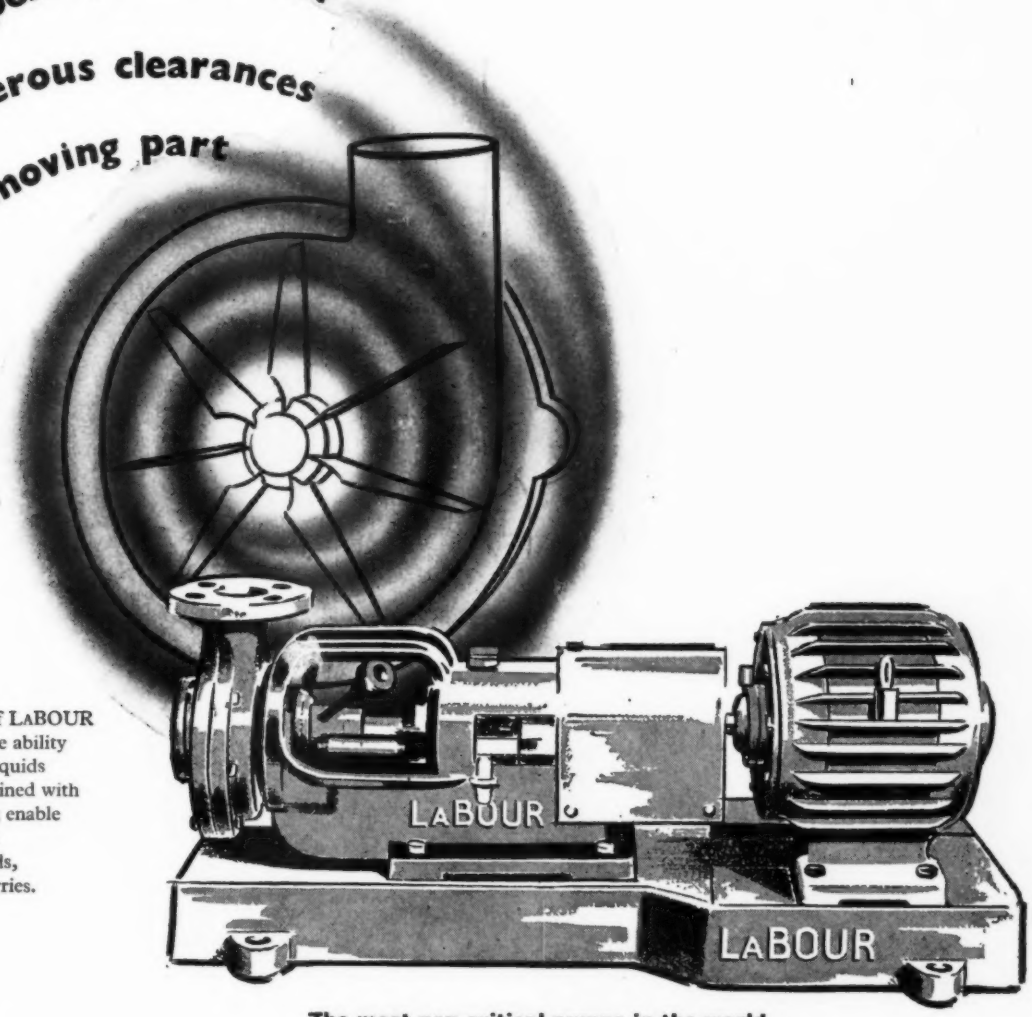

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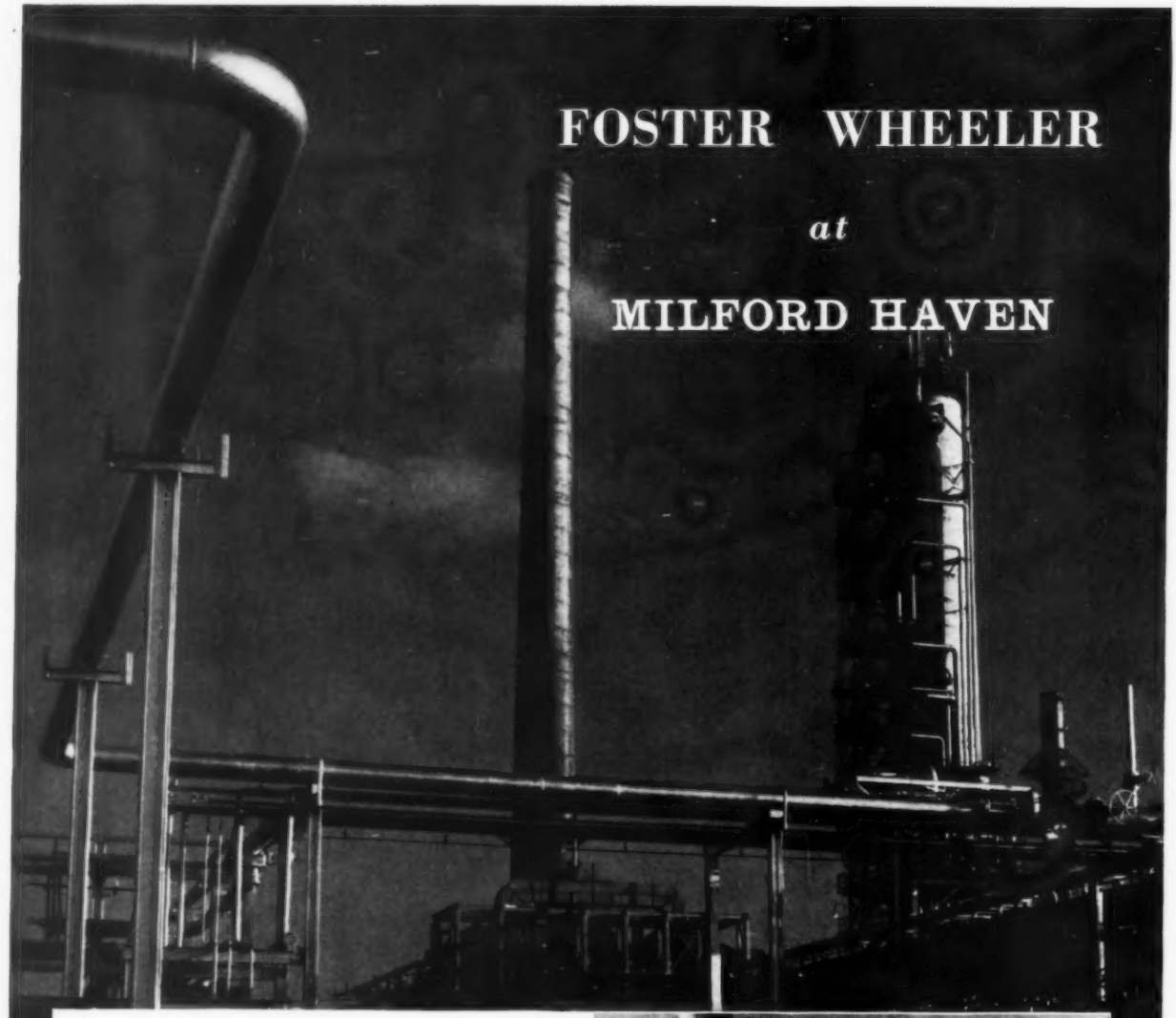

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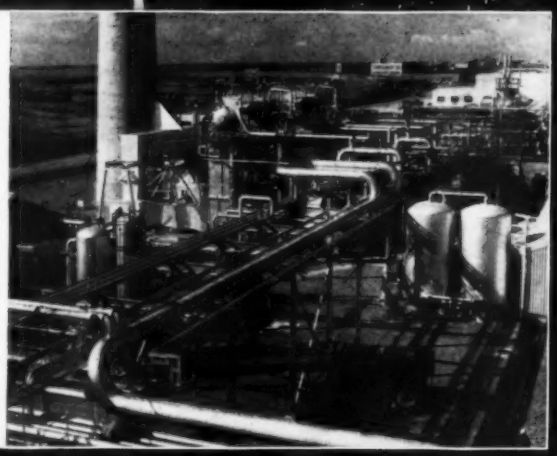

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Problems of the Gas Industry

BY providing a perspective for the future development of the gas industry and, at the same time, by underlining some of the problems, technical and otherwise, which confront the industry, the Autumn Research Meeting of the Institution of Gas Engineers performed an important service.

Today both gas and coal are losing ground to oil, particularly in the heating field, and the competitive power of gas for the future is seen to lie in the ability of the gas industry to sell its main product at a lower price. At present the cost per therm of gas sold to industry is four times the cost per therm based on the pit-head price of coal; on the other hand, the price of a unit from fuel oil is not quite double that based on the pit-head price of coal (3½d. per therm). It can be seen, therefore, that the gas industry, in comparison with its competitors, is at a considerable disadvantage. This has stimulated the development of new methods of gas-making such as the total gasification processes, of which the Lurgi alone has so far reached commercial maturity; it is expected that such processes, operating at a high load factor, will produce gas at less than 9d. per therm.

Here it is as well to indicate some of the technical advantages of gas over alternative fuels. Compared with fuel oil, for example, its utilisation efficiency is higher and its rate of combustion can be more closely controlled. Again, the majority of its consumers are relieved of the need to install extensive storage facilities. One of its outstanding attributes is that it is smokeless, a property of considerable importance in view of the need to reduce air pollution, but one to which, unfortunately, an economic credit is difficult to assign.

A disadvantage is that fixed costs arising from the installation and amortisation of a large distribution system have a considerable influence on production costs and for economy require utilisation at full capacity and with as steady an output as possible. Nevertheless, this is not an insuperable difficulty, since high-pressure processes offer considerable economies in this direction. Thus, it has been shown that the cost of transmitting a given amount of energy a hundred miles in high-pressure pipelines is only a fraction of the cost of transmitting the same amount of energy by high-voltage cable.

The problems of gas and coal are intimately connected, and there is much to be said for the approach which regards coal as an important source of chemicals; thus it is interesting to note that processes under development in Europe take account of the fact that the known deposits of solid fuels contain about twenty times more liquid and gaseous constituents than crude oil and natural gas, constituents which are lost for chemical purposes if the fuel is directly used for steam generation.

These processes, which apply especially to low-grade solid fuels, produce gas, tar and electric power in a sequence of integrated plants, the tars being subsequently used as a source of chemicals such as plastic, synthetic rubber, solvents and so on. One clear advantage of this approach is that although the first cost of the combined power station and gasworks is 30 to 40% higher than that of a condensing power station, it is considerably less than the combined cost of a separate power station and gasworks.

Another approach was suggested by PROFESSOR THRING at the conference, namely the combined use of slagging-type gasifiers for the simultaneous production of pig iron; a process which, from the point of view of iron production, has the advantage of eliminating the coke-oven stage. It is possible that this process, with an oxygen blast and with the appropriate steam addition, could be made to yield a gas of useful calorific value for the gas industry and which would require a relatively small rate of iron production for its economic justification. Other processes are likely to enter the picture; one which is under very active consideration in a number of countries is the gaseous reduction of iron ore by hydrogen and carbon monoxide, a process calling for reducing gases and offering further opportunities for the slagging gasifier. Thus there is much in the belief that the future of gas lies in its closer integration with the process and metallurgical industries on the one hand and power generation on the other.

As things stand at the moment, the development of the gas industry suffers from a number of obstacles. In the first place, at the time of nationalisation, the industry was technically and economically in poor shape. Then, the majority of works, apart from technical backwardness, were of such small size that they were almost certainly beyond economical operation, and fewer than 10% of them were of an economical size. This state of backwardness has had to be eliminated. Second is the attitude of the Government itself to the whole problem of fuel and power, based as it is on the fallacy of freedom of fuel choice for the consumer, a negation of policy which makes the development of the gas industry a gamble, and which, in view of the inroads made by oil into fields previously held by coal and gas, could lead to a situation where oil occupies a position potentially dangerous to the national economy. One consequence could well be the stagnation of coal production, with the result that a future greater demand for coal which might arise, for example, through the development of total gasification and other processes, would be impossible to satisfy. Again, although oil has an important part to play in any integrated scheme, it must be remembered that its purchase has led to a heavy balance of imports over exports, a trend which can be expected to increase if the present standpoint is adhered to. There is, therefore, much to favour adjustment of the refinery programme to yield a far lower proportion of fuel oil and a correspondingly higher proportion of automobile and aviation spirit. Such a change would supply national petrol requirements from half the present import of crude oil.

Another obstacle is evident from the report of the Wilson Committee, for the scale of effort recommended by them for the development of improved methods of gasification is too small in comparison with the magnitude of the problem.

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DEVELOPMENT OF A RADIOACTIVE AEROSOL FOR TESTING FILTER FABRICS

A radioactive aerosol is used for measuring the efficiency of dry filter media. The aerosol particles labelled with $_{15}P^{32}$ were size analysed, and their mass median size was found to be 0.3 micron, with no particles greater than 1.2 micron. The technique used for measuring the efficiencies is described; it is easy and safe, and the reproducibility is good. The technique is applicable to numerous problems in the field of dust filtration, both in the laboratory and on the plant.

by J. K. SKREBOWSKI* and B. W. SUTTON*

Introduction

IN the current development work on bag filters undertaken in this laboratory* it was found necessary to assess accurately the fine dust removal efficiency of various filter fabrics, so that an appropriate fabric could be selected for any specific duty of gas filtration. The method initially tried[1] was that of dispersing a known amount of very fine silica dust (containing 75% by weight less than 5 microns diameter) in air and using the fabric under test to filter the dust cloud. The efficiency of the fabric was determined by measuring the concentrations of dust entering and leaving the filter fabric. This method of testing had two main disadvantages, viz.:

(1) The efficiency of the filter fabric increases rapidly as dust accumulates on its upstream surface; thus the efficiency becomes a function of the quantity of dust used in the test.

(2) The fabrics used in practice for industrial dust filtration purposes are found to have efficiencies all of which approach 100% using this dust.

These two effects make differentiation between fabrics extremely difficult.

Another method which was explored was the British Standard Methylene Blue Test.[2] In this method a dilute (1%) solution of methylene blue dye in water is atomised into fine droplets and the droplets evaporated to dryness; the particles thus produced have a mass median diameter of 0.5 micron. The aerosol which passes through the fabric under test is collected on a white filter paper over a measured period of time, and then treated with steam; a deep blue coloration is produced, the intensity of the colour being proportional to the amount of dye collected on the paper. As a reference standard, another filter paper is used to sample the inlet aerosol stream. The time (found by trial and error) is adjusted so that the same depth of colour is obtained on each filter paper. Then the ratio of the times necessary to produce the same intensity of stain is a quantitative measure of the fabric efficiency.

The methylene blue test largely overcomes the disadvantages of the silica dust test mentioned above, and differentiates well between different fabrics, provided that their efficiencies are not much below 80%. Unfortunately, the colour intensities vary with the way the filter papers are treated with steam after the dye has been collected on the paper surfaces; in addition, the estimation by eye of relative colour intensities is subject to personal error, and the time required to obtain reliable results by this trial and error method is excessive. As the methylene blue aerosol is much finer than the silica dust, the efficiencies of the majority of fabrics are well below the limit of accurate measurement by the methylene blue test (i.e., below 80%), and this limitation virtually excludes the assessment of a large number of industrial fabrics used for dry filtration purposes.

The third method tried[3] was based on the use of a non-pathogenic bacterial aerosol (*Chromobacter prodigiosum*). In this test the aerosol is sampled simultaneously at the inlet and exit of the filter. The impingement collector plate of the standard "slit sampler"[4] is covered with nutrient jelly, and the aerosol concentrations are determined by subsequent incubation and a count of clearly visible colonies. The method has, however, limitations, such as the inevitable delay in obtaining the results due to the length of the incubation period (20-24 hr), and the need for the services of a bacteriologist.

Other types of test aerosol which might be used for testing fabric filters were also considered. Several of these are formed by vaporising organic substances and then condensing the vapours into very fine mists under carefully controlled conditions. The quantity (by weight) produced by condensation is very small, and consequently the collection and quantitative estimation of such a mist requires specialised techniques. Examples of such techniques can be

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CUMULATIVE % BY WEIGHT LESS THAN

found in the references.[5, 6, 7]

Consideration of the results obtained using aerosols of the types described above led to the formulation of the following specification for an aerosol to be used for testing fabric filters:

(1) In the production of the aerosol, size reproducibility is essential.
(2) The average size of the aerosol particles should be in the neighbourhood of $\frac{1}{2}$ micron.
(3) Detection and measurement of minute quantities of aerosol should be simple and accurate.

Conditions (1) and (2) are comparatively easy to fulfil by straightforward adaptation of the "Collison atomiser" system as used in the British Standard Methylene Blue Test. Preliminary experiments with a radioactive aerosol were found to be most promising for the fulfilment of condition (3), and it was decided to concentrate effort on this development.

The Choice of Radioactive Material

The decision to use potassium dihydrogen phosphate (KH_2PO_4) for the aerosol was mainly due to the fact that the labelled compound was available at Billingham, being used for work on radioactive tracers. In addition, this compound is easily soluble in water, which would be useful if it proved necessary to extract the active aerosol from a filter. It is of advantage to use radioactive phosphorus ($_{15}P^{32}$) as a tracer element for several reasons: the half life is fairly short (14 days), but not so short that too-frequent replenishment of supplies is necessary. On the other hand, it is not so long as to be a source of prolonged contamination in the event of spillage. This element ($_{15}P^{32}$) emits only β-rays and these are of low penetrating power; 80 mg of any material per cm^2 will reduce the intensity of the radiation by half. Thus, handling the substance in ordinary glass jars is quite safe, since little radiation will penetrate the walls. Ordinary rubber gloves and forceps afford sufficient protection when handling activated filter papers, etc., especially as the level of radioactivity used for the tests is very low.

The aerosol was produced by the atomisation, with subsequent evaporation of water, of a very dilute solution (0.01% by weight) of KH_2PO_4 in distilled water containing a small amount of KH_2PO_4, labelled with radioactive phosphorus ($_{15}P^{32}$).

Preliminary experiments showed that, on evaporating small droplets of a 0.01% solution of KH_2PO_4 in water, the resulting aerosol was composed of small crystalline particles mostly with diameters below 1 micron. This was considered quite satisfactory for the purpose in mind, and subsequently a size analysis was carried out on the aerosol using a thermal precipitator as a collecting instrument and an electron microscope for sizing the particles.

The size analysis using the electron microscope was carried out by fitting a magnified photographic transparency of a standard graticule on to the screen of the electron microscope and sizing the particles by matching with appropriate circles on the graticule. This method was basically similar to the ordinary size analysis technique using an optical microscope.[8] Size analyses were carried out on three samples taken on different occasions and the results were in agreement. A mean curve was drawn (Fig. 1) which shows that there were no particles larger than 1.2 micron and that the mass median size of the aerosol was 0.3 micron.

The conditions necessary for the production of the aerosol from the "Collison atomiser" were as follows: an air pressure of 30 lb/in² gauge, an air flow of 600 litres/hr, and a concentration of KH_2PO_4 of 0.01% by weight in distilled water at room temperature. Higher concentrations of KH_2PO_4 were tried, but it was found that there was a tendency to form loose clusters of particles of very much larger sizes than 1 micron.

Fig. 2 shows the appearance of the aerosol (produced under standard conditions as specified above) when examined under the electron microscope. All subsequent tests have been made using this standard aerosol.

Apparatus

The apparatus is shown in Fig. 3. It consists of a "Collison atomiser" (using clean compressed air at 30 lb/in² gauge), the description of which is given in [2]. The air pressure to the atomiser, and hence the flow rate, is kept constant at a predetermined value by an automatic pressure-regulating valve; a pressure gauge and a rotameter are also connected to the atomiser. Following the atomiser is a T-junction to a drying tower, through which dry filtered air is drawn to be mixed with the main stream at a rate equal to that from the atomiser (about 600 litres/hr). This ensures that the dew-point of the airstream is low enough to prevent any subsequent condensation of moisture upon the aerosol particles.

The fine droplets are passed through a long metal tube heated to over 100°C, where the remaining water is

Fig. 1. Particle size analysis of the radioactive aerosol (mean curve).

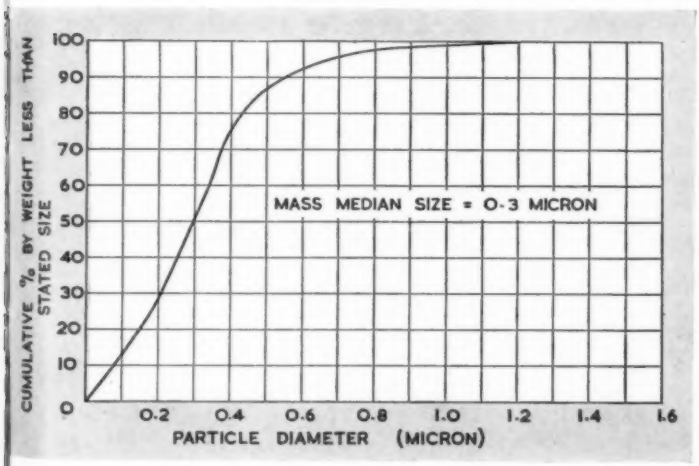
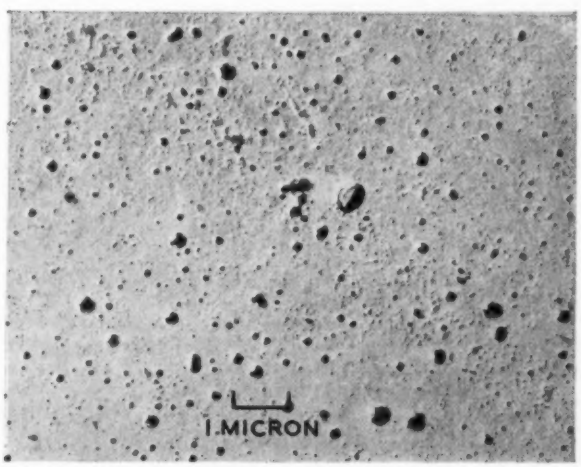


Fig. 2. Electron micrograph of the aerosol; magnification ×7800 (gold shadowed at an angle of 1 in 4).



evaporated, leaving solid material in the form of an aerosol composed of fine particles of KH_2PO_4. The aerosol is now passed through a tube of 2 in. dia. and a portion of it is removed through a sampling nozzle. The remaining aerosol is passed through a superfine glass wool filter (guard filter), then through the by-pass flowmeter and finally vented outside the building. The sampled portion of the aerosol is divided equally into two streams. In the limb carrying one stream a filter-fabric holder of $1\frac{1}{2}$ in. inside dia. containing the fabric specimen to be tested is inserted. It is followed by a brass holder (Fig. 4) containing a replaceable disc of filter paper (Whatman 42) 2 in. dia., which collects the aerosol, followed in turn by a flowmeter and a fine needle valve which is used to adjust the air flow accurately. The other limb is similar but without the filter fabric holder. It was decided to use No. 42 Whatman filter paper following tests with various grades of Whatman filter paper in which it was found that the No. 42 paper had an efficiency greater than 97% and was superior to all the other papers tested.†

The whole apparatus is under suction and the exhausted air, with any remaining trace of radioactive aerosol, is drawn through 100% efficient guard filters (superfine glass-wool) before being vented outside the building.

Additional equipment consists of a Geiger-Müller tube fitted at one end with a mica window of mass per unit area 2 mg/cm². As shown in Fig. 4 (b), the Geiger-Müller tube is fitted into a brass "pot" which positions the tube inside the filter holder with its end window $\frac{1}{4}$ in. from the surface of the filter paper. It is essential that the Geiger-Müller tube be at the same distance from the filter-paper in each holder when measuring the activity collected, and this is ensured by using filter holders of identical dimensions in all tests.

The Geiger-Müller tube is connected by co-axial cable via the probe unit (Ekco Type N.558) to a scaling unit (Ekco Type N.529B).

Experimental Procedure

The heated tube is allowed to reach its equilibrium temperature, and an air rate of 600 litres/hr is set on the by-pass flowmeter. Suction is then applied to both limbs and the air rate to the atomiser is adjusted to 600 litres/hr at 30 lb/in² gauge. At this air rate, approximately 15 ml/hr of the dilute (0.01%) solution of radioactive KH_2PO_4 is atomised. The air flow rates through the limbs are equalised by adjusting the separate needle valves and set at 125 litres/hr to give 0.1 ft/sec. face velocity through the fabric test specimen. The aerosol is passed through the filter for a period of about 15 min., after which the atomiser is switched off, but the air flow is maintained for a further 3-5 min. to purge all lines of the radioactive aerosol. The filter paper holders are then removed, top caps unscrewed, and counting is carried out by inserting the Geiger-Müller tube in its brass "pot" inside the body of the filter holder as shown in Fig. 4 (b). The heavy brass body of the filter holder protects the Geiger-Müller tube from stray radiations from outside. From these measurements the efficiency of the fabric can easily be determined. Normally, when measuring the efficiency of a fabric, about four separate determinations are made, and the average value of the efficiency of the filter fabric is calculated.

Before the test it is advisable to check the equipment for leaks by carrying out the test without a fabric specimen. In such a case the ratio of activities of the papers should be within about ±3% of unity.

In order to obtain convenient counting rates (e.g., about 5000 counts/min. in the "blank" test) it was found necessary to use about 100 ml of solution in the atomiser with a total activity of about 20μC (microcuries).

To calculate the efficiency, if

B = background count (counts/min.),

C_1 = activity of paper in upper limb (counts/min.) (see Fig. 3),

and C_2 = activity of paper in lower limb (counts/min.), then

Inlet Activity $I = C_1 - B$, and

Exit Activity $E = C_2 - B$.

Since activities are proportional to the masses of aerosol collected, then:

$$\text{Efficiency } \eta = \frac{I - E}{I} \times 100\%$$

Reproducibility of Measured Efficiencies

The reproducibility of measurements is affected mainly by two factors: viz., the accuracy with which the flow rate in each limb can be measured, and the random variations in the counting rates observed.

The rotameters used to measure flow rates are calibrated against each other at intervals, but it is doubtful if the indicated rates are reliable to better than ±2%. In the case of the measurements of the counting rates, the accuracy is dependent on the total number of β-emissions counted, the actual relation being that the standard deviation σ for N counts is given by $\sigma = \sqrt{N}$. It can be seen, therefore, that the accuracy of measurement can be increased both by increasing the activity of the sample and by increasing the duration of counting. Practical considerations have led to the choice of a value of N equal to about 50,000 in most cases (e.g., 5000 counts/min. for 10 min.), which gives a standard deviation $\sigma = \pm 224$, i.e., $\pm\frac{1}{2}\%$ for each determination of activity of a filter paper.

In view of these considerations, it can be expected that the scatter found in the "blank" tests will be of the order ±3%.

Table I shows the results of a series of tests on three different fabrics covering a wide range of efficiencies and a series of "blank" tests, analysed to obtain a measure of the reproducibility of the efficiency of each fabric. It can be seen that, as the fabric efficiency increased, the error of the measurement diminished rapidly: the highest errors were obtained in the results of the "blank" tests.

TABLE I—Errors of Measurement

Fabric	Number of Tests n	Mean Efficiency η_i	Standard Deviation σ	Standard Error of the Mean $\left(\eta_i \pm \frac{\sigma}{n}\right)$
Filter paper	7	96.6%	0.9	(96.6 ± 0.3) %
Wool felt	12	75.9%	2.1	(75.9 ± 0.6) %
Woven cloth	12	16.6%	2.4	(16.6 ± 0.7) %
"Blank" tests	12	−0.1%	3.0	(−0.1 ± 0.9) %

The radioactive technique was first developed late in 1956, and the efficiencies of about 100 filter fabrics have since been measured. The results show that the efficiency of a given fabric varies with the face velocity of the aerosol, but the efficiency is not a simple function of the face velocity. At a given face velocity (e.g., 0.1 ft/sec., which was chosen as the standard value in these tests because velocities of this order are commonly used in industrial bag filters) the efficiencies of different fabrics vary over a very wide range; no simple relationship has yet been found between the efficiency of a fabric and its structure; i.e., weave, yarn, weight per unit area and nature of the constituent fibres.

The Efficiency of a Dust Cake Deposited on a Fabric Filter

It is known that when dusty gas is filtered through a fabric filter the efficiency of filtration is constant when the fabric

† Alternatively, other filters, such as layers of superfine glass-wool, can be used as sampling filters, in which case the active aerosol is leached out with a 1% solution of o-phosphoric acid in water and the activity is measured using a Geiger-Müller counter for liquids. This method is, however, less convenient than that described above in the majority of cases.

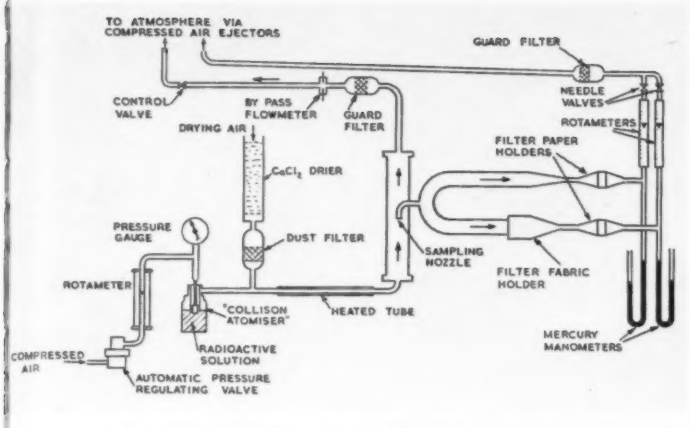


Fig. 3. Diagram of apparatus for testing fabrics with radioactive aerosols.

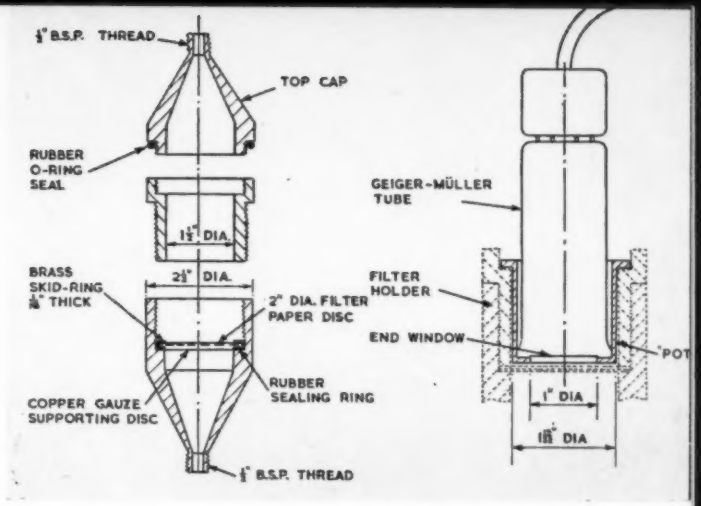


Fig. 4. Diagram of filter paper holder and positioning of Geiger-Müller tube.

is clean, but as dust deposits on the fabric in appreciable quantity it begins to act as an additional filtering medium and the overall efficiency increases considerably.

The efficiency of a clean fabric was measured and subsequently a known quantity of fine silica dust was deposited on it. Its efficiency was then measured without disturbing the dust cake, and again measured after cleaning by blowback.

In this way several fabrics were examined, and the results (in Table II below) show that the dust cake gives rise to an increased filtration efficiency, even after some of the dust has been removed by blowback.

TABLE II—Effect of Deposited Dust on Filtration Efficiency

Fabric	Aerosol Efficiency		
	New Clean Cloth %	After Dust Deposition %	After Cleaning by Blowback %
Lightweight plain cloth (synthetic fibre)	2	65	13
Heavy raised-surface cloth (synthetic fibre)	24	75	66
Heavy raised-surface cloth (natural fibre)	39	82	69

Discussion

The radioactive aerosol method has proved valuable for the determination of fabric filter efficiencies, since it is now possible to measure efficiencies fairly accurately over a range from less than 5% to virtually 100%. By using a radioactive tracer, difficulties encountered with the other techniques investigated have been largely overcome.

The method is sufficiently simple and safe to be used by laboratory personnel after a short course of instruction. The apparatus required is comparatively inexpensive and easy to fabricate, while the equipment needed for measuring the radioactivity is now readily available as a standard item. It is possible to obtain the radioactive tracer material from The Radiochemical Centre, Amersham, at a few days' notice and at a very moderate price.

No special shielding between the apparatus and the personnel is required because of the low penetrating power of the radiation involved and the very low activity of the radioactive material in the apparatus at any given time. Certain safety precautions are, however, observed, such as handling the container for a minimum time, using thick rubber gloves and keeping the whole apparatus under a slight suction, with the atomiser enclosed in a fume cupboard, thus ensuring that no leakage into the laboratory atmosphere can occur. In addition, the effluent from the apparatus is filtered through a 100% efficient guard filter packed with superfine glass-wool before being vented to the atmosphere at roof-top level. The pieces of fabric and filter paper which have become contaminated with radioactivity during the tests are stored in a metal container for several months until the activity has decayed to a negligible value.

The radioactive aerosol test technique has been applied successfully to the elucidation of a number of other problems in the field of dust filtration. The efficiencies of granular and fibrous packed beds used as filters have been investigated in the laboratory and the effects of varying parameters such as face velocity, granule/fibre size and depth of packing were explored; the influence of irrigation on such beds was also examined. The packing materials examined included glass-wool, slag-wool, sand and gravel of various grades, ceramic spheres and pellets. Essentially the same technique has been used to measure the efficiency of a full-size plant filter by injecting the radioactive aerosol into the gas-stream.

In conclusion, it is considered by the authors that the radioactive aerosol technique is an improvement on existing methods of measuring fabric filter efficiencies, and that it is capable of being developed for use in the study of a wide range of other problems in the physics of small particles.

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THE APPLICATION OF STATISTICS TO COST ESTIMATING

by A. P. SHAHBENDERIAN

A method is suggested for obtaining, quickly and accurately, labour cost estimates of chemical plant or equipment. The method requires an analysis of cost data obtained previously for a particular piece of equipment and is illustrated by the example of a mild-steel floating-head heat exchanger. The labour cost is derived from a multiple regression analysis of previous labour costs for this type of exchanger.

THERE is much scope for the application of statistical techniques in the field of cost estimating. Chemical plant manufacturers and other organisations concerned with the cost estimation of equipment, manufactured to a client's specification, are usually faced with the problem of providing both budget and accurate cost estimates.

Budget estimates are usually obtained from graphical correlations of past data, or simply by looking up previous records. Accurate estimates are derived by adding together the probable component costs; viz.: labour, material, design and shipping costs, together with overheads, profits and a contingency cost.

The determination of an accurate *labour* cost involves assessing the times taken by the various sections of the organisation to manufacture the item. For complicated items of chemical plant, labour cost estimating is usually difficult and time-consuming. It is quite often the main hold-up in the compilation of the final selling price for quotation to the client. The problem, therefore, is to reduce the time involved in obtaining labour cost estimates and this can certainly be done by using the methods of multiple regression[1] (sometimes known as the "method of least squares") to analyse past cost data. By analysing previous labour cost data for plant items of a particular category (e.g., heat exchangers), it is possible to deduce equations which will accurately predict the labour cost of a new exchanger of the same category and falling within the range of dimensions of previously fabricated exchangers.

Multiple Regression Analysis of Labour Costs

The labour cost assessment of mild-steel, floating-head heat exchangers will be considered as an example. The labour cost involved in the fabrication of a heat exchanger will be a function of its several characteristics, such as number of tubes, length of tubes, shell diameter, shell thickness, number of baffles and so on.

Expressing this mathematically:

$$C = f(N, L, A, T \ldots) \qquad \ldots . (1)$$

where C = labour cost;
N = number of tubes;
L = length of tubes;
A = shell surface area $= \pi D_s L$, where D_s = shell internal diameter;
T = shell thickness.

Fig. 1 indicates the significance of these characteristics in relation to a typical mild-steel, floating-head heat exchanger.

As an approximation, it is postulated that the labour cost, C, may be expressed by a linear equation of the form:

$$C = a + bN + cL + dA + eT + \ldots \qquad \ldots . (2)$$

where $a, b, c, d, e, \ldots$ are constants.

Thus, the labour cost, C, is taken as independently linearly related to each of the variable characteristics N, L, A, etc. This assumption has been justified by practical experience and will be discussed later.

With labour cost data available for previously manufactured heat exchangers with characteristics N, L, A, etc., known, it is thus possible to produce Equation (2) with the constants, a, b, c, etc., so determined that they are the "statistically best fitting" constants for the known data. It is the author's experience, however, that, in the case of heat exchangers, Equation (2) can be still further simplified to an equation of the form:

$$C = l + mN + pA$$

where l, m and p are constants. This further simplification implies that the labour cost of a heat exchanger is largely conditioned by the two factors—number of tubes (N) and shell surface area (A). The only justification for this further simplification is that the equation $c = l + mN + pA$ has proved to be reasonably accurate in practice. Qualitatively, however, it might be expected that N and A would be the dominating factors in the cost equation. It should also be realised that the other variable characteristics, such as length of tubes, size of nozzles, etc., are directly related to either N and A, and hence the use of N and A alone includes, to some extent, the effects that these other variable characteristics have on the total labour cost.

The problem thus reduces to finding only three "best fitting" constant, l, m and p, from known cost data.

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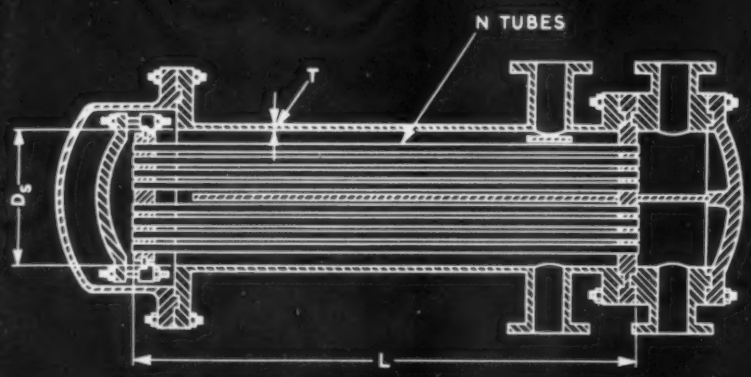

Fig. 1. Cross-section of typical mild-steel floating-head heat exchanger.

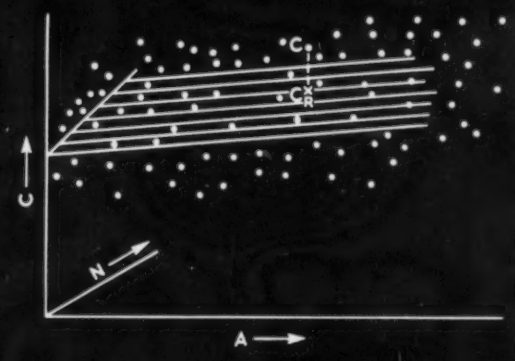

Fig. 2. C shown as a function of N and A. Points scattered about a plane.

If this further simplification were true and the known labour cost data were plotted graphically as a function of N and A, it would be expected that the points would lie roughly in a plane, as shown in Fig. 2.

The extent of the "scatter" from a plane drawn through the points would indicate the validity of the assumption that both N and A were independently and linearly related to C.

It will now be seen that the problem reduces to finding the equation of the "best fitting plane" through the scattered points. This can easily be done using the well-known techniques of multiple regression. The mathematics involved is contained in most standard texts on statistical methods,[1, 2, 3] but it has been reproduced in this article to show that the underlying theory is simple and the necessary computation easy. Statistically, the best fitting plane is such that the sums of squares of the ordinate deviations from this plane ($C - C_R$ in Fig. 2) is a minimum (hence the use of the phrase "method of least squares"). This plane will have intercept l on the C-axis, slope m in the direction of the N-axis and slope p in the direction of the A-axis and will be given by an equation of the form:

$$C_R = l + mN + pA$$

This is known as the regression equation, m and p being the so-called regression coefficients.

As noted above, for any two corresponding values of N and A, the ordinate deviation will be given by $(C - C_R)$. We now have to meet the condition

$$\sum_1^n (C - C_R)^2 = \text{a minimum}$$

for all the n points in the scatter diagram (Fig. 2).

$$\text{Now } \sum_1^n (C - C_R)^2 = \sum_1^n \Big\{C - (l + mN + pA)\Big\}^2$$

The values of l, m and p which make $\sum_1^n (C - C_R)^2$ a minimum are obviously obtained by differentiating separately with respect to l, m and p and equating to zero.

$$\text{Thus } \frac{\partial \Big\{\sum_1^n (C - C_R)^2\Big\}}{\partial l} = -\sum_1^n 2\Big\{C - (l + mN + pA)\Big\} = 0$$

$$\frac{\partial \Big\{\sum_1^n (C - C_R)\Big\}^2}{\partial m} = -\sum_1^n 2N\Big\{C - (l + mN + pA)\Big\} = 0$$

$$\frac{\partial \Big\{\sum_1^n (C - C_R)\Big\}^2}{\partial p} = -\sum_1^n 2A\Big\{C - (l + mN + pA)\Big\} = 0$$

$$\text{i.e. } \sum_1^n C = \sum_1^n l + m\sum_1^n N + p\sum_1^n A \quad \ldots.(3)$$

$$\sum_1^n N \,.\, C = l\sum_1^n N + m\sum_1^n N^2 + p\sum_1^n A \,.\, N \quad \ldots.(4)$$

$$\sum_1^n A \,.\, C = l\sum_1^n A + m\sum_1^n A \,.\, N + p\sum_1^n A^2 \quad \ldots.(5)$$

Now $\sum_1^n C = n \,.\, C_m$, where C_m is the mean of all the n previously known values of C.

Similarly, $\sum_1^n N = nN_m$; $\sum_1^n A = nA_m$

From Equation (3):

$$nC_m = nl + mnN_m + pnA_m$$

$$\text{i.e. } C_m = l + mN_m + pA_m \quad \ldots.(6)$$

i.e., the best fitting plane, called the regression, passes through the means of all the A and all the N values.

Multiplying Equation (6) by nN_m and subtracting from Equation (4) gives:

$$\sum_1^n N \,.\, C - nN_m \,.\, C_m = l\Big\{\sum_1^n N - nN_m\Big\} + m\Big\{\sum_1^n N^2 - nN_m^2\Big\} + p\Big\{\sum_1^n AN - nA_m N_m\Big\} \quad \ldots.(7)$$

$$\text{Now } \sum_1^n N \,.\, C - nN_m \,.\, C_m = \sum_1^n (N - N_m)\,(C - C_m) \quad \ldots.(8)$$

This can be shown by multiplying out, and simplifying, the right-hand side of Equation (8).

$$\sum_1^n (N - N_m)\,(C - C_m) = \sum_1^n N \,.\, C - \sum_1^n N \,.\, C_m + \sum_1^n C_m \,.\, N_m - \sum_1^n N_m \,.\, C$$

$$= \sum_1^n N \,.\, C - n \,.\, N_m \,.\, C_m + n \,.\, N_m \,.\, C_m - \sum_1^n N_m \,.\, C$$

$$\text{But } \sum_1^n N_m \,.\, C = nN_m \,.\, C_m$$

$$\therefore \sum_1^n (N - N_m)\,(C - C_m) = \sum_1^n N \,.\, C - nN_m \,.\, C_m$$

Furthermore, on the right-hand side of Equation (7):

$$\sum_1^n N - nN_m = 0, \text{ since } N_m = \frac{\sum_1^n N}{n}$$

and $\sum_1^n N^2 - nN_m^2 = \sum_1^n (N - N_m)^2$, since:

$$\sum_1^n (N - N_m)^2 = \sum_1^n N^2 - 2\sum_1^n N \,.\, N_m + \sum_1^n N_m^2$$

$$= \sum_1^n N^2 - 2nN_m \,.\, N_m + nN_m^2$$

$$= \sum_1^n N^2 - nN_m^2$$

$\therefore$ Equation (7) reduces to:

$$\sum_1^n (N - N_m)(C - C_m) = m\sum_1^n (N - N_m)^2 + p\sum_1^n (A - A_m)(N - N_m) \quad \ldots . (9)$$

Similarly, with Equations (6) and (4):

$$\sum_1^n (A - A_m)(C - C_m) = m\sum_1^n (N - N_m)(A - A_m) + p\sum_1^n (A - A_m)^2 \quad \ldots . (10)$$

Hence m and p may be determined from the two simultaneous Equations (9) and (10), since it has been assumed that n values of C, N and A are available from previous cost data.

Now, generally, $C_R = l + mN + pA$

and $C_m = l + mN_m + pA_m \quad \ldots . (6)$

Eliminating l:

$$C_R = C_m + m(N - N_m) + p(A - A_m) \quad \ldots . (11)$$

Equation (11) is the equation of the best plane "fitting" the given data, i.e., the equation fitted by the method of least squares. It is now possible to use this equation to predict future costs.

Hence, if the labour cost, C_1, is to be estimated for a new exchanger with N_1 tubes and shell surface area A_1, it can be

TABLE I—Hypothetical Data for Mild-steel Floating-head Heat Exchangers, 0-500 psi Working Pressure

Labour Cost C(£)	Area A(sq.ft)	Number of Tubes N	C^2	A^2	N^2	$A.C$	$A.N$	$C.N$	Compare: Calculated Labour Cost from Regression Equation (£)	Compare: Actual Labour Cost (£)
310	120	550	96,100	14,400	302,500	37,200	66,000	170,500	293	310
300	130	600	90,000	16,900	360,000	39,000	78,000	180,000	315	300
275	108	520	75,625	11,664	270,400	29,700	56,160	143,000	273	275
250	110	420	62,500	12,100	176,400	27,500	46,200	105,000	254	250
220	84	400	48,400	7,056	160,000	18,480	33,600	88,000	220	220
200	90	300	40,000	8,100	90,000	18,000	27,000	60,000	206	200
190	80	230	36,100	6,400	52,900	15,200	18,400	43,700	179	190
150	55	120	22,500	3,025	14,400	8,250	6,600	18,000	127	150
140	64	190	19,600	4,096	36,100	8,960	12,160	26,600	152	140
100	50	100	10,000	2,500	10,000	5,000	5,000	10,000	117	100
$\sum_1^{10}$ 2135	891	3430	500,825	86,241	1,472,700	207,290	349,120	844,800		

$C_m = 213.5$ $A_m = 89.1$ $N_m = 343.0$ $10\,C_mA_m = 190,228.5$ $10\,C_mN_m = 732,305.0$ $10\,N_mA_m = 305,613.0$

$\frac{\left(\sum_1^{10} C\right)^2}{10} = 455,822.5$ $\frac{\left(\sum_1^{10} A\right)^2}{10} = 79,388.1$ $\frac{\left(\sum_1^{10} N\right)^2}{10} = 1,176,490.0$ $\therefore \sum_1^{10} (C - C_m)^2 = 500,825 - 455,822.5 = 45,002.5$

$\sum_1^{10} (N - N_m)^2 = 1,472,700 - 1,176,490 = 296,210$ $\sum_1^{10} (A - A_m)^2 = 86,241 - 79,388.1 = 6,852.9$

$\therefore \sum_1^{10} (C - C_m)(N - N_m) = 844,800 - 732,305 = 112,495$ $\sum_1^{10} (C - C_m)(A - A_m) = 207,290 - 190,228.5 = 17,061.5$ $\sum_1^{10} (A - A_m)(N - N_m) = 349,120 - 305,613 = 43,507$

$\therefore$ Equation (9) gives $112,495 = m(296,210) + p(43,507)$
and Equation (10) gives $17,061.5 = m(43.507) + p(6852.9)$
Hence, $m = 0.2089$ and $p = 1.1634$

TABLE II

(a)	Regression equation: $C = 38.2 + 0.209N + 1.163A$
(b)	Sums of squares due to regression $= 0.209 \times 112,495 + 1.163 \times 17,061.5 = 43,354.0$
(c)	Total sums of squares $= 45,002.5$
(d)	Residual sums of squares $= 45,002.5 - 43,354.0 = 1648.5$
(e)	Estimated residual variance $(S^2) = \frac{1648.5}{10-3} = 235.5$
(f)	Gaussian multipliers $C^{11} = \frac{6,852.9}{296,210 \times 6,852.9 - (43,507)^2} = 0.500 \times 10^{-4}$ $C^{22} = \frac{296,210}{296,210 \times 6,852.9 - (43,507)^2} = 21.615 \times 10^{-4}$ $C^{12} = \frac{43,507}{296,210 \times 6,852.9 - (43,507)^2} = 3.175 \times 10^{-4}$
(g)	Variance (V_1) of an individual estimate $C_1 = 176$, using $N_1 = 240$ and $A_1 = \pi + 1.5 \times 16 = 75.4$ $V_1 = 235.5\left[1 + \frac{1}{10} + 0.500 \times 10^{-4}(240 - 343)^2 + 21.615 \times 10^{-4}(75.4 - 89.1)^2 + 2 \times 3.175 \times 10^{-4}(240 - 343)(75.4 - 89.1)\right]$ $= 690.5$
(h)	Standard error of $C_1 = \sqrt{690.5} = 26.28$
(i)	"t" for 7 degrees of freedom $= 2.36$
(j)	Confidence limits for $C_1 = £176 \pm 2.36 \times 26.28 = £176 \pm £62$

obtained from Equation (11); viz.:

$$C_1 = C_m + m(N_1 - N_m) + p(A_1 - A_m)$$

N_m, A_m and C_m are known from the analysis of existing heat exchangers. To illustrate the computation procedure, suppose ten sets of hypothetical values are known for previously fabricated mild-steel floating-head heat exchangers, with various working pressures in the range 0-500 psi. Table I illustrates the necessary computation.

The values calculated beneath Table I are inserted in Equations (9) and (10) to solve for m and p. Thus Equation (11) is, for this example, given numerically by:

$$C = 213.5 + 0.2089\,(N - 343) + 1.1634\,(A - 89.1) \quad \ldots\ldots (11)$$

or $$C = 38.2 + 0.209N + 1.163A \quad \ldots\ldots (12)$$

Hence, the labour cost of a mild-steel floating-head heat exchanger, 350 psi working pressure, with 240, 16-ft-long, tubes and shell internal diameter of 1 ft 6 in. is given by:

$$C = 38.2 + 0.209 \times 240 + 1.163\,(\pi \times 1.5 \times 16)$$

i.e., C = £176.

Thus it can be seen that the technique of multiple linear regression is very useful in analysing previous cost data to produce equations such as (12) that can be used to predict future costs. The derivation of an equation such as (12) was based on the assumption that the labour cost C is taken as independently linearly related to each of the variable characteristics N, A, etc. As stated previously, this assumption has been justified by practical experience for the case of heat exchangers. Generally, however, it might be expected that this assumption would be valid over a restricted range of equipment sizes. Thus, although the "scatter diagram" might indicate a curved plane over a very large range of equipment sizes, it should be possible to restrict the range such that the plane is approximately "flat" over a small region.

If the linear approximations are found not to be sufficiently accurate, then Multiple Non-Linear Regression equations can be developed by fitting polynomial equations in N and A of the form, e.g.:

$$C = d + eN + fN^2 + \ldots \alpha A + \beta A^2 + \ldots$$

On the other hand, if the cost equations can be expressed in the form $C = gN^aA^b$, then a simple logarithmic transformation reduces the equation to the linear form:

$$\log C = \log g + a \log N + b \log A$$

i.e. $C' = g' + aN' + bA'$, where $C' = \log C$, etc.

This last equation may obviously be analysed in a manner analogous to the equation $C = l + mN + pA$. It should be remembered that in this case the method of least squares minimises the sums of squares of deviations such as ($\log C - \log C_R$), and *not* ($C - C_R$), in a "scatter diagram" (see Fig. 2) of $\log C$ vs. $\log A$ and $\log N$.

Finding the simplest, yet adequate, equation is largely a matter of trial and error, but quite often simple linear equations are found to be sufficiently accurate. In the case of two independent variables, N and A, the computation is relatively short, but with three or more variables the computation can be tedious and it is wise to follow the computational rules supplied in some text-books.[1, 2, 3] The use of a calculating machine is a considerable help.

Accuracy of Estimation

No mention has so far been made concerning the reliability of regression equations, such as Equation (12), derived from past data. For the case of heat exchangers, it is the author's experience that it is possible to produce equations, in the form of Equation (12), which will predict labour costs within an accuracy of 15% of the actual labour cost later incurred. It is, however, important to specify the so-called confidence limits to the accuracy of the regression equation determined from past cost data. For example, if Equation (12) is used to predict the labour cost of a mild-steel floating-head heat exchanger, 350 psi working pressure, with 240, 16-ft-long tubes and shell diameter of 1 ft 6 in., what are the limits, on either side of the calculated cost of £176, within which it can confidently be expected that the actual labour cost will eventually lie? The confidence limits normally chosen on a quantitative basis are the 95% confidence limits; i.e., limits are obtained within which the actual labour cost will lie with 95% certainty. Alternatively, this means that there is a 5% chance that the actual labour cost will lie outside the limits specified. It should be remembered that in comparing finally known labour costs with the original estimates based on the regression equation, it is imperative to ensure that due allowance has been made for any change in labour wages between the time of making the original estimate and the time at which the final cost is known.

It is not possible in this article to derive in detail the formulæ used in assessing the 95% confidence limits for predictions based on the regression equation. The procedure is standardised in most texts.[1, 2, 3] However, the necessary steps are listed below.

Procedure for Calculating 95% Confidence Limits for a Single Observation

For the example given in this article, it is necessary to calculate:

(*a*) *The regression equation:*

$$C = l + mN + pA$$

(*b*) *Sums of squares due to regression:*

$$m\sum_1^n (C - C_m)\,(N - N_m) + p\sum_1^n (C - C_m)\,(A - A_m)$$

where n = number of sets of C, N and A values

(*c*) *Total sums of squares:*

$$= \sum_1^n (C - C_m)^2$$

(*d*) *Residual sums of squares:*

$$= \sum_1^n (C - C_m)^2 - \left\{ m\sum_1^n (C - C_m)\,(N - N_m) + p\sum_1^n (C - C_m)\,(A - A_m) \right\}$$

(*e*) *Estimated residual variance* (S^2)*:*

$$= \frac{\sum_1^n (C-C_m)^2 - \left\{ m\sum_1^n (C-C_m)(N-N_m) + p\sum_1^n (C-C_m)(A-A_m) \right\}}{n-3}$$

(*f*) *Gaussian multipliers:*

$$C^{11} = \frac{\sum_1^n (A - A_m)^2}{\sum_1^n (N-N_m)^2 \sum_1^n (A-A_m)^2 - \left\{ \sum_1^n (A - A_m)\,(N - N_m) \right\}^2}$$

$$C^{22} = \frac{\sum_1^n (N - N_m)^2}{\sum_1^n (N-N_m)^2 \sum_1^n (A-A_m)^2 - \left\{ \sum_1^n (A - A_m)\,(N - N_m) \right\}^2}$$

$$C^{12} = \frac{\sum_1^n (A - A_m)\,(N - N_m)}{\sum_1^n (N-N_m)^2 \sum_1^n (A-A_m)^2 - \left\{ \sum_1^n (A - A_m)\,(N - N_m) \right\}^2}$$

(*g*) *Variance* (V_1) *of an individual estimate* C_1*:*

$$V_1 = S^2 \left\{ 1 + \frac{1}{n} + C^{11}(N_1 - N_m)^2 + C^{22}(A_1 - A_m)^2 + 2C^{12}(N_1 - N_m)\,(A_1 - A_m) \right\}$$

Continued on page 39

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THE CORROSION OF CONDENSER TUBES

by D. G. KINGERLEY*

The identification, mechanism and prevention of the corrosion of non-ferrous condenser tubes are described. Success in preventing attack on the water side was achieved by paying attention to metallurgical and design factors; today, interest is directed towards the steam side, and treatment must be considered in relation to the whole steam-water system

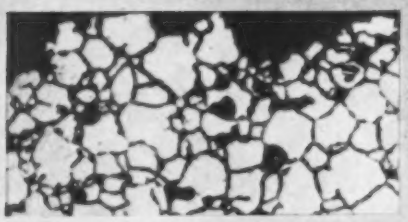

Fig. 1. Photomicrograph of intercrystalline penetration of aluminium-brass by sea-water containing hydrogen sulphide.

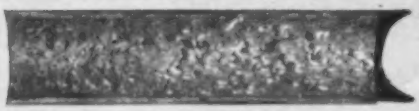

Fig. 2. Corrosion-erosion of brass tube showing characteristic horseshoe-shaped grooves.

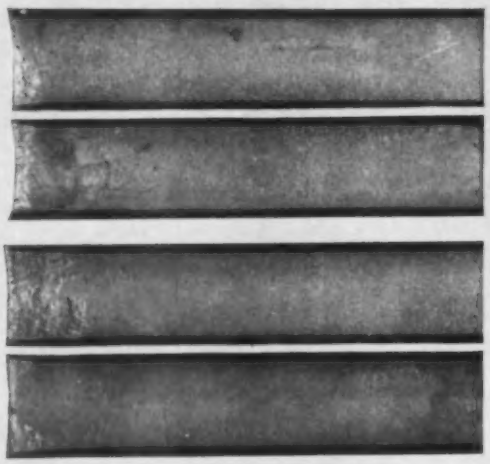

Fig. 3. Corrosion-erosion concentrated at the inlet end of brass condenser tubes.

THE corrosion of condenser tubes was one of the most serious problems in the field of corrosion prevention. It assumed the proportions of a menace in the First World War, when it caused more trouble to British ships than the German Navy,[1] and the reduced availability of present-day giant turbo-generators through condenser tube failure represents a serious economic loss.

Usually, condenser tubes have been manufactured from copper or copper-base alloys because of the excellent resistance to corrosion, high thermal conductivity and favourable physical properties of these materials. After a few days' service, products of initial corrosion form on the tube surface. If these are insoluble, impervious, continuous and adherent, they offer protection against further corrosion. If, however, these conditions are not fulfilled, corrosion will proceed.

A condenser tube which has failed exhibits characteristics indicative of the cause of failure. These fall into three groups: the tube is uniformly thinner as a result of general wastage; the tube is deeply pitted as a result of localised attack; or the tube is cracked, perhaps with little loss of metal, as a result of stress.

These groups may be subdivided further, but the initiation and progress of any form of attack depends upon such factors as condenser design, operating conditions, composition of cooling water, and the particular tube alloy bringing into prominence certain of the fundamental principles underlying the corrosion of non-ferrous metals and alloys. Some of these principles may be conveniently mentioned now. Thus, salt solutions in the presence of an oxidising agent will cause metallic corrosion unless the corresponding salt of the metal is insoluble and can protect the metal from further attack. Access of oxygen assists the formation of a protective oxide film on the surface of zinc and, thus, has an ennobling effect, whereas a deficiency of oxygen renders zinc more anodic.

Oxygen has relatively little ennobling action on the already high potential of copper, except at low liquid speeds. Even so, the natural potential of copper is much higher than that of zinc artificially ennobled by aeration. Immersion in fast-moving solutions also has different effects on copper and zinc; it aids corrosion of copper by stimulating release of metal to maintain the equilibrium number of ions in solution and, in accordance with the Moto-Electric Effect, by

* Has recently gained his Associate Membership of the Institute of Fuels and works with the Central Electricity Generating Board, Derby.

imposing anodic behaviour with respect to another region of the same metal not exposed to such liquid movement.

In contrast to the behaviour of copper, the electrode potential of zinc is almost independent of the concentration of zinc ions in solution when this concentration is low. Thus, the cells which may operate include:

Brass, Solution, Aerated Solution, Brass.
And Brass, Stagnant Solution, Moving Solution, Brass.

Again, a metal under strain will have a different value of electrode potential from the same unstrained metal immersed in the same solution, and although a properly drawn tube surface is structureless,[2] removal of metal by corrosion will eventually expose a less ordered region. At such parts of the tube, grain boundaries are often potentially anodic centres, and if stifling by insoluble corrosion products cannot occur more severe attack begins. This is particularly so in heavily polluted waters when intergranular penetration proceeds.

The season-cracking of brass containing residual stresses in the presence of ammonia and oxygen results from the formation of soluble complexes containing copper ions which continually shift the potential of copper in the negative direction. In the alpha-beta brasses, the zinc-rich beta phase often suffers anodic attack on chloride solutions and the preferential corrosion of a network of beta grains surrounding an area of alpha phase can cause great damage by allowing the relatively unattacked alpha region to fall out of place.

Corrosion of homo-phase alloys is often governed by the principle of Parting Limits.[3] Preferential removal of the base metal leaves an accumulation of the noble constituent which prevents further attack. This results in chloride solutions not attacking the alpha brasses any more severely than pure copper.

General Wastage

General wastage leads to uniform thinning of the tube and is not responsible for as many tube failures as the more localised forms of attack. Corrosion occurs because water conditions preclude the formation of a protective film and proceeds by means of a continuous dissolution of the metal, and high concentrations of certain substances have been shown to result in serious general wastage.

Hydrogen sulphide, originating from industrial waste, sewage or the action of sulphate-reducing bacteria, principally vibrio desulphuricans, covers the surface of brass tubes with a voluminous, insoluble, but non-protective black layer. Anaerobic conditions favour the bacterial action, which is thus more likely at low water velocities and under layers of deposit on the tube. Seasonal variations in corrosion have been shown to be proportional to the concentration of hydrogen sulphide in the water.

Treatment of the cooling water with substances such as chlorine and acriflavine to eliminate the bacteria has proved remedial, but is impossible on board ship and, except in the case of chlorination, is uneconomic for land installations operating on open circuit. Carbon dioxide also forms a non-protective scale and when present in a concentration high relative to oxygen leads to severe attack. Thus, in one instance, of the new tubes of 70/30 brass put into service in June some 40% underwent pitting within a month, whereas the majority of a number of similar tubes installed in the following November had not failed after two years. In this case the "aggressive" carbon dioxide was incapable of dissolving the protective film which had accumulated during the winter months, although this is not always so.

Higher summer temperatures appear to be a contributory factor to season variations in corrosion, since laboratory exposure of brasses to a 3% sodium chloride showed that a temperature rise of 10°C doubled the corrosion rate.

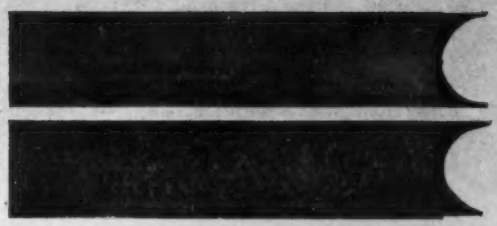

Fig. 4a. Aluminium-brass tube showing resistance to corrosion-erosion under conditions which attacked an arsenical brass tube (4b).

Fig. 5a. 70/30 brass tube punctured by severe local corrosion-erosion caused by partial blockage.

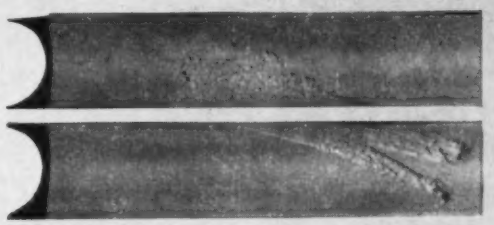

Fig. 5b. The result of severe corrosion-erosion of aluminium brass early in the tubes' service.

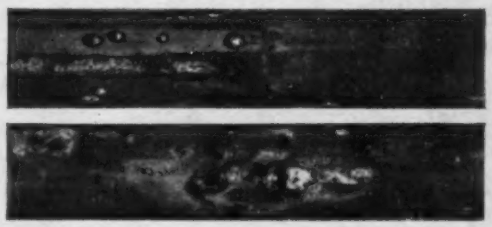

Fig. 6. Deposit attack. The scabs of corrosion products conceal the pits.

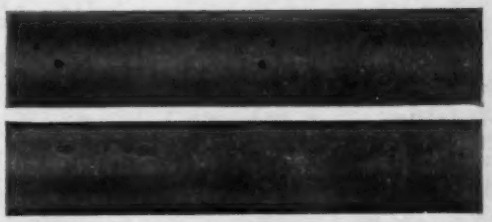

Fig. 7. Plug-type dezincification, showing both inner and outer surfaces of a non-arsenical brass tube.

The presence of acids, perhaps from industrial effluents, in the cooling water usually leads to soluble products of corrosion, and wastage proceeds. In the case of the brasses, the effect of liquid movement on the corrosion of copper comes into operation. When the concentration of oxygen is low, as in acid mine waters, such agents as the ferric ion are capable of fulfilling a similar role and corrosion still occurs. It has also been shown that cupric salts acting as oxygen carriers accelerate the corrosion of copper by dilute acids.[4] The metal, undergoing attack, reduces cupric ions to the cuprous state from which the divalent condition is achieved with the aid of oxygen. The cycle is then repeated. A similar mechanism probably operates in the corrosion of copper by ammonia,[5] in the presence of oxygen, the ammonia sometimes arising from bacterial action in the cooling water.

Heavily polluted waters lead to intercrystalline attack, and it is believed that the presence of larger amounts of arsenic, antimony or particularly phosphorus, than are necessary for the inhibition of dezincification, render the tube susceptible to such penetration (Fig. 1). The presence of large quantities of hard, solid particles, such as sand, in the cooling water occurs under certain estuarine conditions. This material has an abrasive action, comparable to "shot blasting", on the tube surface, particularly the lower side, and assists in the removal of the protective film. Although abrasion is not itself a form of corrosion, it prepares the way for it. Incorrect cleaning of the tubes with, for example, hard wire brushes has a similar effect and should be avoided.

There are two main types of localised attack: corrosion-erosion and deposit attack.

Corrosion-erosion

Corrosion-erosion, or impingement attack, often produces crescent- or horseshoe-shaped grooves on the tube surface, with the bend of the horseshoe pointing upstream; the grooves, often undercut, are usually free of corrosion products. The first few inches of the inlet end of the tubes are often the only damaged areas, although in severe cases attack occurs along the entire length of the tube. Intense local attack at any other point usually results from a partial tube blockage close to the point of corrosion (Figs. 2, 3, 4b and 5).

The corrosion is due to conjoint chemical-mechanical action in fast-moving turbulent water. In a tube of $\frac{3}{4}$ in. diameter the flow of water becomes turbulent when the velocity reaches 2.2 ft/sec. The velocity in land condensers is usually 5-7 ft/sec, and that in marine installations about 15 ft/sec. Thus turbulence always exists. Sudden changes in direction of flow and in cross-sectional area of the induction-system will increase this turbulence and tend to release dissolved gases from solution, thereby forming bubbles. These gases will be redissolved with difficulty. Thus the tube surface will be subjected to suction when low pressure regions are formed. When a bubble in contact with the tube collapses, the movement away from the metal produces a suction, but the rapid movement of water towards the wall results in an impact upon it. Considerable damage to the protective film thus occurs, and the bare metal is exposed to corrosive attack by the cooling water. Also, some adherence of film to bubbles probably takes place. At certain places, particularly at the inlet end or near a local obstruction, the tube is constantly exposed to corrosion-erosion in this way and depolarisation of cathodic areas by air in the bubbles may also contribute to corrosion. Serious cases of impingement attack have caused failure in a few weeks of particularly susceptible tubes such as 70/30 brass or Admiralty mixture. Very aggressive cooling waters also contribute to early failure.

The use of higher water speeds in large modern installations led to more trouble from this form of attack, and therefore called for more attention to be paid to the design of such units.

The design of water-boxes, injection nozzles and piping should be streamlined to avoid sudden, angular changes in direction, low pressure pockets, and any other obstruction to smooth flow, which may cause local high velocity and increased turbulence. The shape of sacrificial anodes of iron, steel or zinc, for example, when these are used to confer cathodic protection from galvanic attack on the tube-end plates, must be considered in this respect. Streamlined entry into the tubes is assisted by the use of flush-fitting ferrules, or by expanding the tubes at the inlet end, and countersinking the tube ends to allow a flush fit into the tube plate. The injection nozzle should gradually increase in area and curve smoothly into the water-box, which should be vented to by-pass air into a section of the discharge pipe at lower pressure. Similar care should be directed towards the circulating pumps. The presence of barriers in the vortices has been shown to prevent funnelling of the water, and sealing the glands with water at higher pressure prevents the entry of air.

Temporary methods of prevention of attack include the coating of the tube surface with a bituminous preparation, or a paint containing zinc dust. Such measures reduce heat transfer to some degree, and in the former instance are not applicable in tropical waters. When impingement attack is confined to the inlet end of the tube lead inserts have been used with success, and recently these have been manufactured from a plastic material.

Advances in Protection

The most successful advances in protection have been metallurgical. For example, the presence of 2% of aluminium in 70/30 brass increases the resistance to corrosion-erosion.[6] But this addition raises the fictitious zinc content; therefore, to preserve the alpha structure, more copper must be added. This gives an aluminium-brass containing 76% copper, 22% zinc and 2% aluminium, and this type of alloy has resisted impingement attack entirely, undergoing only slight dezincification, under conditions which attacked an arsenical 70/30 brass, and caused an arsenic-free brass to suffer severe dezincification (Figs. 4a and 4b).

Electrode potential measurements showed the projection to be due to a self-healing film on the metal. The potential decreases if the aluminium-brass is scratched, but quickly rises to a noble value as the film of aluminium oxide, possibly hydrated, is reformed.

Brasses without aluminium are covered by no such film. The presence of 0.02% of arsenic is still necessary if the tube is to be immune from dezincification and this amount does not affect the resistance to corrosion-erosion.[7] The resistance of bronzes containing more than a 10% content of tin is due, probably, to a similar protective film, capable of self-repair.[8]

Very severe impingement attack will damage an aluminium-brass tube because the film will be unable to reform under the rapid bombardment (Fig. 5). This is especially the case with a newly-installed tube if the film has not developed completely, and under such conditions one of the cupro-nickel alloys is likely to be more resistant.

Alloys of copper with 10, 15, 20 and 30% of nickel have also been used, and although their introduction took place at much the same time as that of aluminium-brass, the manufacturing difficulties are greater. Of the pure cupro-nickel alloys, resistance to corrosion increases with the nickel content, and again results from a hydrated oxide film which develops on the surface during the first few days' immersion in water. The surface film is strengthened by the addition of 0.75% each of iron and manganese to the alloy, and increasing each of these additions to 2% improves the

resistance to corrosion even more. Additions of this magnitude to a 90/10 cupro-nickel tube confer corrosion-resistance equivalent to that of a 70/30 cupro-nickel which does not contain iron and manganese.

The performance of tubes of varying nickel content, with and without these additives, during the past twenty years has given rise to much argument about their relative merits, but the most resistant of them is probably 70/30 cupro-nickel with 2% of each additive.[9] This alloy is usually recommended for estuarine waters of high suspended solids content, condition which would cause aluminium brass to fail; in addition, the cupro-nickel alloys are less prone to fatigue-failure.

Contemporary use of titanium under estuarine conditions will provide data for further comparisons. Its general resistance to both corrosion and fatigue is well known, and titanium tubes have shown remarkable immunity from attack under corrosion-erosion conditions during trials.

Deposit Attack

This form of corrosion occurs on brass tubes as pits, often containing cuprous oxide, under or adjacent to various foreign bodies or regions of corrosion products, particularly non-protective sulphide scale (Fig. 6).

These foreign bodies, such as stones, twigs, leaves, molluscs, sand particles, algæ and oil drops, in combination with a low cooling water velocity are the causes of this kind of attack. These conditions permit the differential aeration cell to operate. The region of metal screened by the deposit becomes anodic to the unscreened area, to which air has more access. Severe pitting results when a small deposit is surrounded by a much larger area of cathodic undamaged film.

According to another viewpoint, corrosion starts at fortuitous breaks in the protective film, perhaps caused by the deposit on arrival; the corrosion products adhere to the deposit and thus are prevented from arresting further attack on the tube. It is also thought that products of decomposition of organisms assist in corrosion, although it is not known yet whether any organisms can function as cathodic depolarisers on non-ferrous tubes. Removal of the deposit does not always prevent attack from continuing, owing to the tendency of copper to corrode more rapidly in faster moving water.

Thirty years ago, under the conditions favouring deposit attack, particularly when the oxygen content of the cooling water was low, a frequent cause of tube failure was dezincification of the brass. Beneath the corrosion product, often discoloured white basic zinc salts, the brass was converted to copper either in small plugs penetrating the tube wall (Fig. 7), or over large areas of tube surface giving the appearance of a copper-lined brass tube.

The electrochemical explanation of this phenomenon presupposes an initial attack on both the copper and zinc constituents of the brass, and the tube alloys then in use were susceptible to such corrosion, for both Muntz metal and insufficiently heat-treated alpha brass contain the potentially anodic zinc-rich beta phase,[10] and can undergo dezincification in chloride solutions especially. There then remains a small amount of residual copper together with local corrosion products containing basic salts of both zinc and copper.

The electrolytic cell—brass, solution containing copper salts, copper—can operate under these conditions. At the brass anode both copper and zinc ions pass into solution, allowing oxygen equivalent to the zinc, to undergo cathodic reduction to hydroxyl ions. However, an amount of copper electrochemically equivalent to that dissolving at the anode is redeposited on the cathodic copper-rich areas. Such a mechanism is not hindered by any consideration of Parting Limits and to the extent that the presence of copper salts in the corrosion products is essential for its initiation, the mechanism is autocatalytic. The redeposited copper has little mechanical strength and the plugs produced are often porous. BENGOUGH, who proved the redeposited nature of the copper, preferred the term "Apparent Dezincification" for this corrosion mechanism.

The presence of 0.02% of arsenic in alpha-brass prevents[11] dezincification, both copper and zinc salts appearing in the corrosion products. Antimony and phosphorus in similar amounts also confer such immunity without altering the mechanical properties of the alloy. The protection afforded to a homophase brass which has undergone correct heat treatment and contains a dezincification inhibitor is explained by the absence of an overall excess of zinc, and of high local concentrations. Thus, potentially anodic zinc-rich spots are few and a small concentration of inhibitor prevents dezincification. More detailed information is given by electrode potential measurements on the cells:[12]

Brass, concentrated sodium chloride, dilute sodium chloride, brass,

Brass, moving sodium chloride, stagnant chloride, brass,

Brass, sodium chloride, cuprous chloride, copper

showed that there was little difference in the currents developed whether the electrodes used were non-arsenical brass or contained 0.02% of arsenic. But the use of arsenical brass in the cell:

Brass, unaerated sodium chloride, aerated sodium chloride, brass

gave a smaller current than non-arsenical brass.

This suggests the importance of the differential aeration cell in this type of attack. Experiments with a modified form of Brennert apparatus suggest that the protection afforded is due to a film of arsenic, or arsenious oxide, which prevents anodic dissolution of copper without interfering with copper deposition when the brass is made cathodic.

Whilst the use of arsenical brass largely prevents apparent dezincification, resistance to other forms of corrosion is not increased.

Resistance to Dezincification

No dezincification inhibitor has been found for the alpha-beta brasses, and bismuth actually stimulates such preferential corrosion of Muntz metal. This is probably because, in the heterophase alloys, the entire beta-phase is potentially anodic and a small amount of additive is unlikely to prove successful.

The tendency to dezincify is resisted better by brasses of low zinc content and, of course, by copper tubes. Such materials, however, are susceptible to other forms of corrosion. Thus, red brass (85% copper, 15% zinc) falls in this category, being also more immune to stress-corrosion cracking than those containing more zinc. Arsenical copper (0.15-0.5% arsenic), which has a high fatigue limit, and deoxidised copper (99.9 plus) have both been used successfully in fresh water, but have failed rapidly under other conditions. With the cupro-nickel alloys the problem of dezincification does not arise. A form of preferential attack, analogous to dezincification, on the aluminium-bronzes has been reported.

The more general problem of deposit attack can be solved entirely by preventing the entry of foreign bodies into the tubes. Adequate screening of the cooling water is common practice and very small objects which escape this process are removed by frequent brushing of the tubes. Chlorination kills algæ and small shellfish and so prevents their growth on the tubes. The resistance of aluminium-brass to deposit attack is increased by the presence of 0.04% of arsenic, a larger amount than is necessary for the inhibition of dezincification. The high tin-bronzes containing 12% of tin offer good resistance, and their performance as well

as that of the cupro-nickel alloys is enhanced by a pre-treatment in oxygenated sea-water before installation.

In the absence of solid foreign bodies, a type of deposit attack which may still occur is known as Benedicks' Hot Wall action. This form of localised corrosion appears, in the first instance, as green nodules of copper corrosion product covering pits containing cuprous oxide crystals, and occurs on the sites of repeated bubble formation such as scars on the tubes.

The important difference in mechanism from corrosion beneath extraneous solid matter is that here the presence of oxygen in the bubbles induces cathodic behaviour of the metal so screened.

The tube surface on the water side of the bubble periphery will undergo anodic attack if the protective film is weakened in any way. When the oxygen content of the bubble is exhausted, the nitrogen remains, and the mechanism is reversed and conditions are analogous to those in the presence of a solid object. The possibility of corrosion products adhering to the bubble-water interface rather than stifling further reaction also exists, along with that of local increases in concentration of corrosive constituents of the water accompanying bubble formation. But the main danger from this type of attack is the accelerating effect of heat on the corrosion reactions.

The remedy is to increase the velocity of the cooling water and thus prevent the local overheating which leads to bubble formation. Further, the more common use now of tubes which owe their corrosion resistance to a well-developed protective film which does not become greatly roughened in service helps to eliminate such conditions.

Off-load condensers containing stagnant water will suffer similar corrosion, although less severely in the absence of heat, beneath bubbles. Thus, the cooling system should be filled with clean water when the set is out of commission for any length of time.

The above considerations apply to the water side of steam-condensers. Brief mention must be made of the use of tinned tubes before attention is centred on the corrosion of the steam side.

Tinned brass tubes, which were once in widespread use, have been subjected to all of these conditions, and their resistance appears to depend greatly on the type of water, being greater in sea-water. In certain fresh waters, however, the corrosion rate increases rapidly when the tin has been removed, probably because the alloy layer formed during tinning acts cathodically with respect to the tube alloy.

Corrosion of the Steam Side of the Tubes

The design of condensers sometimes allows the accumulation of concentrations of incondensible gases, principally ammonia, but also sulphur dioxide and carbon dioxide. Very corrosive solutions may thus form, being sufficiently strong to cause a deep grooving, even of unstressed brass (Fig. 8).

Copper tubes, similarly, are dissolved away where a film of such liquid meets them.

Relatively minor changes in design usually prevent the formation of these gas-pockets, although in severe cases the use of a cupro-nickel alloy is necessary.

Anti-corrosive measures on the steam side must be considered along with their possible effect on the whole system. For instance, the corrosion of feed-lines varies from a general wastage, due to carbon dioxide (indicated by low pH) and small amounts of oxygen, to localised pitting when large amounts of oxygen are present. In severe cases, the metallic oxides so removed travel to the boiler and cause intense corrosion there. It is therefore desirable to remove these gases or to inhibit their action.

The amount of carbon dioxide in the condensate depends upon the composition of the raw water and upon the type

Fig. 8. Incondensable gases: grooving of brass caused by ammonia.

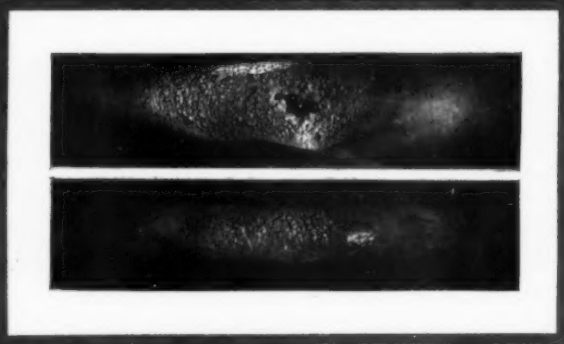

Fig. 9. Steam erosion: impingement of steam on the tubes.

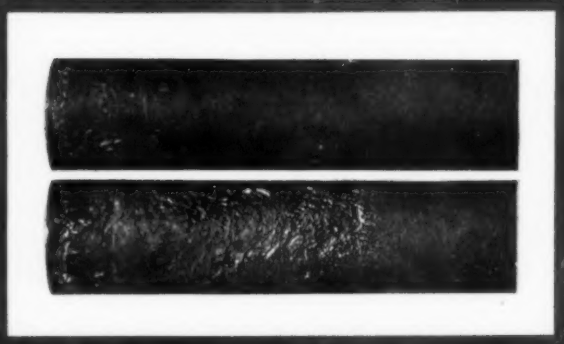

Fig. 10. Corrosion-erosion of the tubes on the steam side caused by leaking ferrule packings.

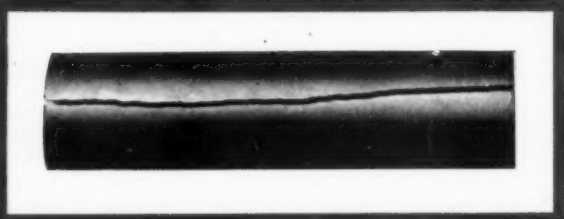

Fig. 11. Stress-cracking: the result of static stress. Branching cracks are common with this fault.

Fig. 12. Fatigue-cracking: the result of alternating stress. Copper alloys mostly suffer transcrystalline cracking.

of treatment used for the boiler feed-water, since water containing free carbon dioxide, carbonates or bicarbonates liberates carbon dioxide on heating and certain chemical treatments.

Water which is untreated, or conditioned in the boiler with sodium carbonate, caustic soda (alone or in conjunction with phosphate) or certain tannins, liberates carbon dioxide into the steam. The hot lime-soda process produces a greater reduction in the carbon dioxide content than precipitation in the cold, and hot lime/zeolite is even better. Simple base-exchange, however, removes none.

The sodium carbonate in the feed-water from any of these methods of softening is hydrolysed to caustic soda in the boiler to a degree depending upon the temperature and pressure and is given by the Straub curves. Base-exchange/acid and H/Na ion exchange followed by degassing and, often, by mixed-bed demineralisation leave only a trace of carbon dioxide. Generally, however, some carbon dioxide will remain in the feed-water.

Oxygen enters the system both in make-up water and through leaks in the condensate and feed systems.

Efficient mechanical (thermal) deaerators are available which remove oxygen down to 0.002 ppm, and it has been stated[14] that chemical scavenging is unnecessary in conjunction with such equipment under steam conditions of 900 psi and 900°F. When such high performance plant is not available, various chemical methods can be used to inhibit the effect of oxygen and carbon dioxide. Injection of caustic soda or sodium phosphate into the steam has been tried in order to produce an alkaline condensate, but contaminated steam is undesirable for much process work, and in steam-turbine practice clean steam is necessary to avoid blade deposits.

Although these objections do not apply to the addition of ammonium salts to boiler-water when the ammonia evolved combines with carbon dioxide and so increases the alkalinity of the condensate, there exists the possibility of corrosion of copper-base alloys used for fittings as mentioned above. (The reason why German systems using ammonia were free from corrosion is that steel tubes and components were widely used at that time.)

Scavengers for oxygen have been used in the form of tannins, sodium sulphite and hydrazine. Tannins are still widely used at lower boiler pressures and have the advantage of promoting easy removal of old scale. With the intensification of steam conditions, the objections to sodium sulphite are the high weight-ratio (sodium sulphite : oxygen = 8 : 1) and its decomposition above 500°F into reducing material (sulphide) and sulphur dioxide, both of which attack brass.

Hydrazine Treatment

Recent work on the use of hydrazine is encouraging: of the three reactions known to occur in a boiler undergoing treatment, the first (a), hydrazine, removes oxygen at the expense of no increase in dissolved solids and the volatile hydrazine increases the alkalinity of the system. Next (b) ferric oxide under the influence of hydrazine is converted to magnetite (but is reduced no farther[15]) and so produces a solid reserve of deoxidant. Finally (c), the decomposition of excess hydrazine to nitrogen and ammonia is negligible below 350°F.

Only (c) has been considered to be unfavourable,[16] and STRAUB states that more than 0.02 ppm excess hydrazine leads to the liberation of dangerous amounts of ammonia; he therefore advocates the use of hydrazine in conjunction with sodium sulphite.

In this country the use of hydrazine has reduced corrosion of feed lines, and has arrested corrosion in feed water-heaters.[17]

The volatile amines, cyclohexylamine and morpholine, can be introduced to the condensate in amounts sufficient to combine with the carbon dioxide and to leave a slight excess to produce an alkaline condition. A decreased tendency to corrode has been observed in that rates of copper pick-up were reduced,[18] and copper pick-up is stated to be greater with morpholine than with cyclohexylamine.[19]

Yet more recently, filming amines have been used. These substances, of which octadecylamine is typical, form a monomolecular, water-repellent layer on the metal surface and inhibit the attack of corrosive agents. Filming amines are insoluble in water, and must be added as a dispersion. They are without effect on pH or conductivity, but are precipitated by highly alkaline conditions. Excellent results have followed their use, and they are to be preferred at high carbon dioxide contents to neutralising amines, which would then be needed in large quantities.

A further advantage to be had with filming amines is their promotion of dropwise, rather than filmwise, condensation and consequent increase in the conduction of heat through the surface.

Steam erosion is not a true form of corrosion, and is due to a mechanical wearing of the tubes by impingement of steam, usually at auxiliary inlets (Fig. 9). It may be prevented by the introduction of baffles.

Impingement attack of the external tube surface occurs when the ferrule packings leak, and follows the mechanism described for this form of attack on the internal surface (Fig. 10). Corrosion is prevented by re-packing the tubes to correct the leaks.

The Effect of Stresses

The presence of stresses leads to early tube failure, which is accelerated by corrosive media. Conditions which in the absence of stress cause pitting will cause fissure-formation and lead to an intensification of stress when a state of strain exists. Static stresses may be residual, which is unlikely with modern methods of manufacture, or applied, as a result of incorrect installation. Such a condition leads to intercrystalline cracking of the tube, usually along its length (Fig. 11).

Fatigue cracking occurs under conditions which impose an alternating stress on the tube such as vibration or large changes of temperature. The cracks are trans-crystalline and usually run across the tube (Fig. 12). Modifications to the design to prevent the vibration, or the operating conditions, when large temperature changes are thought to be responsible, reduce the risk of this type of failure.

ACKNOWLEDGMENTS

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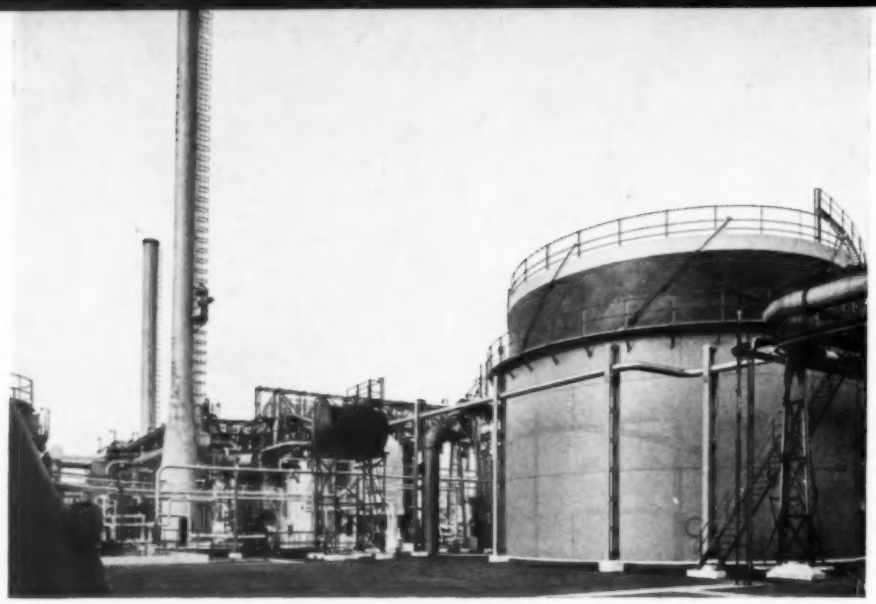

A catalytic oil-gas plant at Romford; before purification, appreciable quantities of water vapour have to be removed in a cooler-condenser. (Photo by courtesy of the North Thames Gas Board.)

THE COOLING AND DEHUMIDIFICATION OF MANUFACTURED GAS

In this article a design method is developed which, in conjunction with tabulated values of properties of the town-gas water vapour system, may be applied in reverse, without trial and error procedures, to obtain coefficients from performance data for cooler-condensers employed by the gas industry. The formation of fog in such plant is discussed quantitatively

by G. S. CRIBB*

1. Introduction

TOWN gas, as manufactured from coal, oil or other hydrocarbons, contains water vapour originating from one or more of five sources. CRADDOCK[1] discusses in detail the contribution from moisture in the fuel, oxygen in the fuel, steam addition to the gas-making unit and evaporation of aqueous liquor brought into intimate contact with the gas as it leaves the gas-making unit. In the catalytic gasification of hydrocarbons, there is a further source of water vapour. It is possible to absorb oxygen on to the catalyst during the blow cycle, which reacts with the hydrogen and carbon in the feedstock during the make cycle, to form water vapour and carbon monoxide and dioxide. The resulting dewpoint of the manufactured gas may vary from 140°F, for horizontal retorts without scrubber standpipes, up to 190°F for certain types of catalytic oil gas plants. In horizontal retort settings there is no steam addition and unless scrubber standpipes are fitted, most of the sensible heat is dissipated before the gas is contacted with liquor in the hydraulic main. The temperature of the gas leaving the catalyst bed in catalytic processes (870°C) is higher than in carbonising processes. In addition, the gas is accompanied by appreciable quantities of water vapour comprising undecomposed steam and water formed by the hydrogen-oxygen reaction. If none of this sensible heat is recovered in a regenerator, the evaporation of circulating liquor in the sprays and wash box is over twice that occurring on a carburetted water gas plant.

Before the gas can be purified, the dewpoint or saturation temperature must be lowered in a cooler-condenser and an approach of 5°F to the cooling water temperature is considered to be a suitable basis for the design of such a unit. The mechanism involved is that of simultaneous heat and mass transfer, and in a previous paper[2] a method was developed for combining the two driving forces into a single potential for the transfer of total heat or enthalpy. Such a method is well established for the design of cooling towers, where the combined potential approximates to the enthalpy of the moist air. The two simplifying assumptions which permit this approximation are that the ratio of heat to mass transfer coefficients is equivalent to the humid heat of the moist air ($h_G/k_G S=1$) and that humidity is the driving force for mass transfer. Unfortunately, neither of these assumptions holds for the dehumidification of hydrogen-rich gases over the temperature range specified.

2. The Theory of Simultaneous Heat and Mass Transfer for the System Water-Town Gas

Values for the ratio h_G/k_G (E) and the humid heat (S) have been experimentally determined, for a typical town gas, using a specially constructed hygrometer in conjunction with a wetted-wall column.[3] The dimensionless group $h_G/k_G S$, known as the Lewis number, was approximately 1.5 over the range of temperature considered, namely 75-90°F. E was 32.3 Btu/(S.G.V.)°F and S 21.1 Btu/(S.G.V.) °F,

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the latter value being in good agreement with that obtained by expressing S as the sum of the specific heat of the dry gas (20 Btu/(S.G.V.) (°F)) and the specific heat of the water vapour carried (0.45 H). As the saturation temperature of the gas approaches 200°F the humidity, and thus the humid heat, increases sharply, e.g., at 180°F, S is equal to 42.1 Btu/(S.G.V.) °F; thus it is evident that S cannot be equated to the transfer coefficient ratio E.

Above 120°F the fraction of the enthalpy change in saturated gas that is attributable to sensible heat is less than 10% and the major error in taking the enthalpy of moist gas as the potential for total heat transfer is the assumption that humidity difference is the driving force for mass transfer. The true driving force or potential difference for the steady state diffusion of one gas through a second stagnant gas is given by SHERWOOD and PIGFORD[4] as

$$\ln [(P - p_G)/(P - p_i)]$$

This may be rewritten as

$$\ln \left(\frac{P}{P - p_i}\right) - \ln \left(\frac{P}{P - p_G}\right) \quad \ldots . (1)$$

The humidity difference $H_i - H_G$ is equal to

$$\left(\frac{p_i}{P - p_i}\right) - \left(\frac{p_G}{P - p_G}\right) \quad \ldots . (2)$$

Comparing the two expressions, the true potential for mass transfer is the humidity multiplied by a factor α where

$$\alpha = \left[\ln \left(\frac{P}{P - p}\right)\right] \Big/ \left(\frac{p}{P - p}\right) \quad \ldots . (3)$$

Values of α are listed in Table I and it will be observed that the assumption of humidity as the driving force is a reasonable approximation up to 100°F. The error at higher temperatures may be gauged from a consideration of mass transfer driving force between saturated gas at 180°F and gas in equilibrium with water at 160°F. The humidity difference (Table I) is 49.19 − 22.39 = 26.80 lb/(S.G.V.). The true driving force is (0.686 × 49.19) − (0.819 × 22.39) = 15.40 lb/(S.G.V.). The error is therefore 75%.

The partial pressure difference expressed in terms of water vapour concentration in the mixture of gas and water vapour is 23.94 − 15.12 = 8.82 lb/1000 cu ft of space. The convention "lb/cu ft of space" is a method of expressing a vapour pressure as a weight/volume concentration. For example, a humidity of 49.19 lb/(S.G.V.) corresponds to 2.73 lb moles of water vapour associated with 2.59 moles of carrier gas. The humidity values apply only to a total pressure of 30 in. Hg, but the partial pressure of water vapour, namely 0.513 atm. or 15.39 in. Hg, is independent of the total pressure. At a total pressure of P atm. the mole fraction of water will be $0.513/P$, but at this pressure, 1000 cu ft will be occupied by $2.59\,P$ moles of the mixture, containing 2.59×0.513 moles of water vapour or 23.94 lb. Thus the vapour pressure of water at any temperature may be expressed as a weight/volume concentration which is independent of pressure. It will be observed that the partial pressure driving force is less than the true driving force and the correction factor applied is termed the "log mean partial pressure of the non-diffusing gas" which, in this case, is equal to 0.576 expressed as a fraction of the total pressure. Hence the true driving force by this method is 8.82/0.576 = 15.31 lb/(S.G.V.).

The slight discrepancy in the values arises from the fact that the α values in Table I are based on the vapour pressures of water from the steam tables of KEENAN and KEYES.[5] The humidity values, on the other hand, have been taken from SPIERS[6] and are not based on the same vapour pressure values.

The use of the correction factor α in conjunction with humidity thus enables the driving force for mass transfer to be expressed accurately as the difference of a potential which may be combined with temperature.

The sensible heat transfer is given by

$$-GSdt_G = h_G (t_G - t_i)\, dA \text{ or } h_G \triangle t dA \quad \ldots . (4)$$

The mass transfer is given by

$$-GdH_G = k_G [(\alpha H)_G - (\alpha H)_i]\, dA \quad \ldots . (5)$$

$$\text{or } k_G \triangle (\alpha H)\, dA$$

The enthalpy of moist coal gas may be expressed as:

$$i_G = S(t_G - t_O) + \lambda_O H_G \quad \ldots . (6)$$

$$= c_G(t_G - t_O) + c_v H_G(t_G - t_O) + \lambda_O H_G \quad \ldots . (7)$$

Differentiating *w.r.t.* to temperature, considering H and t as variable

$$d_{iG} = c_G dt + c_v H_G dt + c_v d H_G(t_G - t_O) + \lambda_O dH_G \quad \ldots . (8)$$

$$= Sdt + [c_v(t_G - t_O) + \lambda_O]\, dH_G \quad \ldots . (9)$$

The second term may be rewritten in terms of λ_i, the latent heat at the interface temperature, since this is the temperature at which the condensing vapour gives up its latent heat.

$$\therefore di_G = Sdt + c_v\, dH_G\, (t_G - t_i) + \lambda_i\, dH_G + c_L\, (t_i - t_O)\, dH_G \quad \ldots . (10)$$

The significance of the four terms on the R.H.S. of Equation (10) is as follows:

Sdt is the sensible heat change in the bulk of the gas; $c_v\, dH_G\, (t_G - t_i)$ is the sensible heat accompanying the diffusing vapour; $\lambda_i\, dH_G$ is the latent heat of the water vapour condensing at the interface temperature t_i and $c_L(t - t_O)\, dH_G$ is the sensible heat above 32°F (t_O) of the water transferred.

If there is an appreciable transfer of matter across the

Symbols Used

A "standard gas volume" (S.G.V.) is equivalent to 1000 cu. ft of gas saturated with water vapour at 60°F and a pressure of 30 in. of mercury.

A = area of transfer surface [ft²];
B *and* C = integration constants;
E = ratio of transfer coefficients h_G/k_G [Btu/(S.G.V.) (°F)];
G = gas flow [(S.G.V.)/hr];
H = humidity [lb/(S.G.V.)];
K = overall coefficient of enthalpy or mass transfer [Btu/ft² hr ($\triangle\theta$)] or [lb/ft² hr ($\triangle\alpha H$)];
L = mass flow of liquid [lb/hr];
P = total pressure [in. Hg];
Q = flow of total heat [Btu/hr];
$R = S/(d_{iG}/dt)$;
S = humid heat $c_G + c_v H$ [Btu/(S.G.V.) °F];
U = overall heat transfer coefficient [Btu/ft² hr °F];
V = water velocity [ft/sec]
a = dimensionless factor, $GdHc_v/h_G\, dA$;
b = differentiation constant;
c = specific heat [Btu/(S.G.V.) °F] or [Btu/lb °F];
d = pipe diameter [in.];
f = dimensionless factor, $a/(e^a - 1)$;
h = film heat transfer coefficient [Btu/ft² hr °F];
i = enthalpy of gas [Btu/(S.G.V.)];
k = film coefficient of enthalpy or mass transfer [Btu/ft² hr ($\triangle\theta$)] or [lb/ft² hr ($\triangle\alpha H$)];
m = slope of chord $(\theta_i - \theta_L)/(t_i - t_L)$ [Btu/(S.G.V.) °F];
m' = slope of chord $(i_G - i_i)/(t_G - t_i)$ [Btu/(S.G.V.) °F];
m_o = slope of tangent $d\theta/dt$ [Btu/(S.G.V.) °F];
p = partial pressure of diffusing vapour [in. Hg];
q = heat flux through gas film [Btu/hr ft²];
t = temperature [°F];
z = fractional distance through the gas film;
α = humidity correction factor;
λ = latent heat [Btu/lb];
θ = enthalpy transfer potential [Btu/(S.G.V.) °F].

Subscripts

G = gas phase condition or temperature;
i = interface condition or temperature;
L = liquid phase condition or temperature;
O = reference condition (32°F) except in case of m_o;
V = vapour phase condition.

TABLE I—Humidity and Enthalpy Data for Town Gas Saturated with Water Vapour

Temperature, °F t	Humidity lb/(S.G.V.) H	Enthalpy Btu/(S.G.V.) i	Enthalpy Transfer Potential Btu/(S.G.V.) θ	dH/dt	di/dt	$d\theta/dt = m$	Humid Heat Btu/S.G.V. °F S	Correction Factor α
40	0.390	581	675	0.0162	37.67	48.8	20.18	0.996
41	0.406	616	723	0.0165	37.99	49.1	20.18	0.996
42	0.422	652	772	0.0168	38.34	49.5	20.19	0.996
43	0.439	689	822	0.0172	38.79	49.9	20.20	0.995
44	0.457	727	872	0.0176	39.24	50.3	20.21	0.995
45	0.475	767	924	0.0182	39.90	50.7	20.21	0.995
46	0.493	808	975	0.0187	40.46	51.3	20.22	0.995
47	0.512	850	1028	0.0192	41.02	52.0	20.23	0.995
48	0.531	893	1081	0.0198	41.69	52.7	20.24	0.994
49	0.552	937	1134	0.0204	42.35	53.3	20.25	0.994
50	0.573	982	1189	0.0212	43.24	54.0	20.26	0.994
51	0.594	1027	1243	0.0220	44.13	54.8	20.27	0.994
52	0.618	1073	1299	0.0229	45.12	55.7	20.28	0.994
53	0.641	1119	1356	0.0238	46.12	56.5	20.29	0.993
54	0.665	1166	1413	0.0248	47.23	57.3	20.30	0.993
55	0.691	1213	1472	0.0257	48.23	58.2	20.31	0.993
56	0.711	1261	1531	0.0266	49.23	59.1	20.32	0.993
57	0.744	1310	1591	0.0275	50.23	60.0	20.34	0.992
58	0.771	1359	1652	0.0284	51.24	61.0	20.35	0.992
59	0.799	1410	1713	0.0293	52.24	62.1	20.36	0.992
60	0.829	1462	1776	0.0307	53.25	63.0	20.37	0.991
61	0.860	1515	1839	0.0312	54.37	64.0	20.39	0.991
62	0.891	1569	1904	0.0322	55.48	65.0	20.40	0.991
63	0.923	1625	1970	0.0322	56.60	66.0	20.42	0.991
64	0.957	1682	2036	0.0342	57.72	67.0	20.43	0.990
65	0.992	1741	2104	0.0352	58.84	69.1	20.45	0.990
66	1.028	1800	2172	0.0362	59.97	69.2	20.46	0.990
67	1.065	1861	2242	0.0374	61.39	70.3	20.48	0.989
68	1.103	1924	2313	0.0388	62.87	71.3	20.50	0.989
69	1.142	1989	2385	0.0402	64.44	72.5	20.51	0.988
70	1.183	2055	2459	0.0416	66.01	73.7	20.53	0.988
71	1.225	2120	2534	0.0429	67.46	75.0	20.55	0.987
72	1.269	2190	2611	0.0442	68.93	76.3	20.57	0.987
73	1.314	2260	2689	0.0455	69.23	77.5	20.59	0.986
74	1.360	2330	2767	0.0468	71.85	79.0	20.61	0.986
75	1.408	2410	2848	0.0483	73.54	80.5	20.63	0.985
76	1.457	2480	2929	0.0498	75.23	82.0	20.66	0.985
77	1.507	2550	3012	0.0518	77.46	83.5	20.68	0.984
78	1.559	2630	3097	0.0528	78.61	85.1	20.70	0.984
79	1.613	2710	3183	0.0545	80.52	86.8	20.73	0.983
80	1.669	2790	3271	0.0562	82.44	88.5	20.75	0.983
81	1.727	2870	3359	0.0580	84.46	90.3	20.78	0.982
82	1.787	2950	3451	0.0600	86.70	92.0	20.80	0.981
83	1.848	3040	3545	0.0620	88.97	94.0	20.83	0.980
84	1.910	3130	3639	0.0640	91.22	96.0	20.86	0.979
85	1.975	3220	3736	0.0660	93.48	97.9	20.89	0.979
86	2.042	3320	3834	0.0683	96.07	99.9	20.92	0.978
87	2.111	3420	3953	0.0705	98.55	102.0	20.95	0.978
88	2.183	3520	4083	0.0727	101.04	104.0	20.98	0.977
89	2.256	3620	4142	0.0750	103.64	106.0	21.02	0.976
90	2.332	3730	4249	0.0773	106.26	108.0	21.05	0.976
91	2.410	3840	4357	0.0798	107.07	110.0	21.08	0.975
92	2.490	3950	4468	0.0823	111.9	112.2	21.12	0.975
93	2.573	4060	4582	0.0848	114.7	114.5	21.16	0.974
94	2.659	4180	4697	0.0874	117.7	116.8	21.20	0.973
95	2.747	4300	4816	0.0899	120.5	119.3	21.24	0.972
96	2.837	4420	4936	0.0927	123.7	121.8	21.28	0.971
97	2.930	4550	5059	0.0954	126.8	124.0	21.32	0.970
98	3.027	4680	5185	0.0983	130.1	127.0	21.37	0.969
99	3.128	4810	5312	0.1010	133.1	129.0	21.41	0.968
100	3.234	4940	5444	0.1040	136.5	132	21.46	0.967
101	3.338	5070	5580	0.1070	140.0	135	21.50	0.966
102	3.446	5210	5710	0.1099	143.4	138	21.55	0.965
103	3.557	5350	5850	0.1132	147.0	141	21.60	0.964
104	3.672	5500	5990	0.1161	150.3	144	21.65	0.963
105	3.790	5650	6140	0.1196	154.3	147	21.71	0.962
106	3.912	5810	6280	0.1233	158.5	150	21.76	0.961
107	4.038	5970	6440	0.1271	162.9	153	21.82	0.959
108	4.168	6140	6590	0.1314	167.8	156	21.88	0.958
109	4.302	6310	6740	0.1362	173.2	160	21.94	0.957
110	4.440	6490	6910	0.1407	178.3	163	22.00	0.955
111	4.583	6670	7070	0.1457	184.0	166	22.06	0.954
112	4.731	6860	7240	0.1500	188.9	170	22.13	0.953
113	4.884	7050	7410	0.1550	194.6	173	22.20	0.952
114	5.042	7250	7590	0.1597	200.0	177	22.27	0.951
115	5.205	7460	7770	0.1648	205.7	181	22.34	0.949
116	5.372	7670	7960	0.1699	211.7	185	22.42	0.948
117	5.544	7890	8140	0.1744	216.8	189	22.50	0.946
118	5.721	8110	8330	0.1806	223.9	194	22.58	0.944
119	5.904	8330	8520	0.1865	230.6	198	22.66	0.942
120	6.093	8560	8730	0.1923	237.3	203	22.74	0.941
121	6.288	8800	8930	0.1984	244.3	207	22.83	0.938
122	6.489	9050	9130	0.2046	251.4	212	22.92	0.936
123	6.697	9310	9350	0.2114	259.1	217	23.01	0.935
124	6.911	9570	9560	0.2177	266.1	222	23.11	0.933
125	7.132	9840	9790	0.2248	274.7	227	23.21	0.932
126	7.359	10120	10010	0.2317	282.4	232	23.32	0.929
127	7.594	10420	10230	0.2389	290.7	237	23.42	0.927
128	7.837	10700	10490	0.2458	298.6	243	23.53	0.925
129	8.088	11000	10740	0.2536	306.9	248	23.64	0.923
130	8.347	11310	10970	0.262	317.2	254	23.76	0.921
131	8.613	11620	11240	0.269	325.3	260	23.88	0.919
132	8.887	11950	11500	0.279	336.8	266	24.00	0.917
133	9.171	12290	11780	0.289	348.2	272	24.13	0.914
134	9.465	12650	12050	0.300	360.8	279	24.26	0.911
135	9.769	13020	12330	0.311	373.5	286	24.40	0.907
136	10.086	13400	12620	0.322	386.1	293	24.54	0.905
137	10.414	13800	12910	0.334	399.9	301	24.69	0.903
138	10.745	14210	13220	0.346	413.6	309	24.84	0.900
139	11.106	14630	13520	0.358	425.4	317	25.00	0.897

TABLE I—Humidity and Enthalpy Data for Town Gas Saturated with Water Vapour (continued)

Temperature, °F t	Humidity lb/(S.G.V.) H	Enthalpy Btu/(S.G.V.) i	Enthalpy Transfer Potential Btu/(S.G.V.) θ	dH/dt	di/dt	$d\theta/dt = m$	Humid Heat Btu/S.G.V. °F S	Correction Factor α
140	11.47	15060	13840	0.370	441.3	325	25.16	0.894
141	11.85	15490	14160	0.381	454.0	334	25.33	0.892
142	12.24	15940	14500	0.393	467.8	343	25.51	0.889
143	12.64	16420	14840	0.407	484.0	352	25.69	0.886
144	13.05	16920	15200	0.421	500.1	361	25.87	0.883
145	13.48	17440	15560	0.437	518.5	370	26.07	0.880
146	13.93	17990	15930	0.455	539.2	380	26.27	0.876
147	14.39	18760	16320	0.473	559.9	390	26.48	0.872
148	14.87	19130	16710	0.491	580.6	400	26.69	0.869
149	15.37	19710	17120	0.511	603.7	410	26.92	0.865
150	15.89	20300	17530	0.532	627.8	420	27.15	0.861
151	16.40	20940	17970	0.555	654.3	431	27.38	0.858
152	17.00	21600	18410	0.577	679.7	444	27.65	0.854
153	17.59	22290	18890	0.597	702.8	456	27.92	0.850
154	18.19	23000	19330	0.618	727.1	471	28.19	0.846
155	18.82	23740	19820	0.642	754.8	487	28.47	0.842
156	19.48	24510	20320	0.670	787.1	504	28.77	0.837
157	20.16	25320	20840	0.698	819.4	522	29.07	0.833
158	20.87	26160	21360	0.728	854.0	543	29.39	0.827
159	21.61	27030	21900	0.758	888.7	562	29.73	0.823
160	22.39	27940	22470	0.792	927.9		30.07	0.818
161	23.20	28870	23040	0.824	964.9		30.44	0.813
162	24.05	29840	23640	0.862	1008.1		30.82	0.808
163	24.93	30870	24250	0.900	1052.7		31.22	0.803
164	25.85	31960	24880	0.943	1102.3		31.63	0.798
165	26.82	33110	25520	0.989	1154.4		32.07	0.792
166	27.83	34320	26190	1.035	1208.6		32.52	0.786
167	28.89	35570	26870	1.087	1268.6		33.00	0.780
168	30.00	36870	27580	1.143	1333.3		33.50	0.774
169	31.17	38220	28310	1.201	1403.3		34.03	0.768
170	32.40	39630	29070	1.268	1478.0		34.58	0.763
171	33.69	41080	29840	1.33	1549.0		35.16	0.755
172	35.05	42630	20640	1.40	1630.4		35.77	0.748
173	36.49	44310	31480	1.48	1722.8		36.42	0.741
174	38.01	46100	32330	1.56	1815.3		37.10	0.734
175	39.61	48000	33220	1.65	1919.4		37.82	0.726
176	41.31	50000	34130	1.74	2023.6		38.59	0.719
177	43.11	52110	35090	1.84	2139.3		39.40	0.711
178	45.01	54360	36080	1.96	2278.0		40.25	0.703
179	47.03	56690	37120	2.09	2418.3		41.16	0.694
180	49.19	59150	38190	2.23	2590.1		42.14	0.686
181	51.50	61700	39360	2.39	2775.1		43.18	0.677
182	53.96	64400	40550	2.54	2948.8		44.28	0.667
183	56.60	67300	41740	2.74	3179.9		45.47	0.659
184	59.45	70700	43020	2.96	3434.3		46.86	0.648
185	62.52	74640	44320	3.18	3688.7		48.10	0.638
186	65.82	78600	45750	3.43	3978.0		49.60	0.627
187	69.39	82800	47230	3.71	4301.3		51.25	0.616
188	73.25	87150	48780	4.02	4660.7		53.00	0.605
189	77.46	91850	50380	4.40	5100.2		54.90	0.593
190	82.07	97300	52030	4.83	5597.4		56.90	0.580

gas film, then the sensible heat conveyed by the diffusing vapour must be taken into account, since the temperature profile is altered. The following treatment parallels that of ACKERMANN[7] and COLBURN and DREW.[8]

The heat flux q at any point in the film may be written as the sum of two terms

$$q = h_G\, dt/dz - G\,(dH_G/dA)\, c_v\,(t - t_i) \quad \ldots.(11)$$

The first term on the R.H.S. of Equation (11) is the heat flux arising from temperature gradient, z being the fractional distance through the film measured from the interface. The second term is the net sensible heat accompanying the diffusing vapour. Since the humidity is decreasing as the gas passes through the cooler condenser (dH_G/dA) is negative. Heat cannot accumulate in the film, so q is constant and Equation (11) may be rewritten:

$$dt/dz + a\,(t - t_i) = \text{a constant } q/h_G \quad \ldots.(12)$$

where $a = -GdH_G\, c_v/h_G dA$.

Differentiating with respect to z

$$d^2t/dz^2 + a\, dt/dz = 0 \quad \ldots.(13)$$

Let $t = e^{bz}$, then $d^2t/dz^2 = b^2e^{bz}$ and $dt/dz = be^{bz}$ from Equation (13)

$$e^{bz}\,(b^2 + ba) = 0;\ \therefore\ b = -a.$$

Thus the solution of Equation (12) is

$$t = B\,e^{-az} + C \quad \ldots.(14)$$

applying the boundary conditions ($z = 0,\ t = t_i$) and ($z = 1,\ t = t_G$)

$$\left.\begin{aligned} t_i &= B + C \\ t_G &= Be^{-a} + C \\ e^{-a}\,t_i &= Be^{-a} + Ce^{-a} \end{aligned}\right\} \quad \begin{aligned} &\therefore\ B = (t_G - t_i)/(e^{-a} - 1) \\ &\text{and } C = (e^{-a}\,t_i - t_G)/(e^{-a} - 1) \end{aligned}$$

From Equation (14) $dt/dz = -aBe^{-az}$

$$= -a(t_G - t_i)e^{-az}/(e^{-a} - 1)$$

when $z = C,\ t = t_i$

$$\therefore\ dt/dz = -a\,(t_G - t_i)/(e^{-a} - 1)$$

substituting in Equation (12)

$$-a\,(t_G - t_i)/(e^{-a} - 1) + a\,(t_i - t_i) = q/h_G$$

$$\text{or } q = h_G\,(t_G - t_i)\,a/(1 - e^{-a}) \quad \ldots.(15)$$

Now a, by definition, is equal to $-GdH_G\, c_v/h_G dA$, or introducing Equation (5), a is equal to $k_G c_v\,(\triangle\, \alpha\, H)/h_G$.

Thus $a = c_v\,(\triangle\, \alpha\, H)/E \quad \ldots.(16)$

where $\triangle\, \alpha\, H = [(\alpha\, H)_G - (\alpha\, H)_i]$ and $E = h_G/k_G$.

c_v and E may both be considered as constants, namely 0.45 Btu/lb and 32.3 Btu/(S.G.V.) °F respectively. The maximum value for $\alpha\, H$ up to 190°F is 47.7 lb/S.G.V. Thus for this temperature range a lies between 0 and 0.67.

The effect of the diffusing vapour is taken into account by rewriting Equation (15) as follows:

$$-GSdt_G - GdH_G\, c_v\,(t_G - t_i) = h_G\,(t_G - t_i)\,a\, dA/(1 - e^{-a}) \quad \ldots.(17)$$

Thus the heat transfer coefficient is increased by the factor $a/(1 - e^{-a})$, but the quantity of sensible heat to be transferred is increased by the amount $-GdH_G\, c_v\,(t_G - t_i)$, equal to $h_G\, a\, dA\,(t_G - t_i)$. The net effect is to decrease the coefficient h_G, as regards transferring the quantity of heat $-GSdt_G$, by a factor f equal to:

$$a[1/(1 - e^{-a}) - 1] \text{ or } a/(e^a - 1),$$

$$\text{i.e. } -GSdt_G = h_G(t_G - t_i)\ adA/(e^a - 1) \quad \ldots.(18)$$

Equation (18) may be rearranged to give:

$$-GSdt_G = h_G\,(t_G - t_i)\,dA\,[1 - (e^a - 1 - a)/(e^a - 1)] \quad \ldots (19)$$

$$\text{or } -GSdt_G + GdH_G\,c_v\,(t_G - t_i)\,[(e^a - 1 - a)/(e^a - 1)\,a] = h_G\,(t_G - t_i)\,dA \quad \ldots (20)$$

It will be observed from Fig. 1 that the term $[(e^a - 1 - a)/(e^a - 1)\,a]$ decreases from 0.50 to 0.444 as a increases from 0 to 0.67, thus assuming the worst case; namely saturated gas at 190°F in contact with water at 60°F. The second term in Equation (10) would be GdH_G (0.45 × 130 × 0.444) or 26 GdH_G Btu. This is small compared with the latent heat term $GdH_G\,\lambda_i$ which is 1060 GdH_G Btu at 60°F, thus in the equation for total heat transfer, the effect of the diffusing vapour may be ignored.

The true heat balance is given by Equation (21):

$$Gdi_G = Lc_L\,dt + dLc_L\,(t_L - t_o) \quad \ldots (21)$$

where by mass balance

$$dL = GdH_G \quad \ldots (22)$$

the expression for the quantity of condensate formed.

Combining Equation (21) with Equation (10) and omitting the term $Gc_v\,dH_G(t_G - t_i)$,

$$Gdi_G = GSdt_G + GdH_G\lambda_i + GdH_G\,c_L\,(t_i - t_o) = Lcdt_L + dLc_L(t_L - t_o).$$

Since $c_L\,(t_i - t_L)$ is always very small compared with λ_i, $GdH_G\,c_L\,(t_i - t_o)$ is approximately equivalent to $dLc_L\,(t_L - t_o)$; thus the simplified heat balance is:

$$Gsdt_G + G\,dH_G\,\lambda_i = Lc_L\,dt_L \quad \ldots (23)$$

This equation is the basis for combining the heat and mass transfer Equations (4) and (5) as follows:

$$G\,[h_G\,(t_G - t_i) + k_G\,\lambda_i\,\{(\varkappa H_G - (\varkappa H_i\}]\,dA = h_L\,(t_i - t_L)\,dA \quad \ldots (24)$$

The L.H.S. of Equation (24) may be simplified by expressing it as a difference of potential θ, where θ is given by

$$E\,(t - t_o) + \varkappa H\,\lambda$$

$$\therefore\ Gdi_G = k_G\,(\theta_G - \theta_i)\,dA = h_L\,(t_i - t_L)\,dA \quad \ldots (25)$$

In deriving this expression for total heat transfer, which forms the basis of the design method by CRIBB and NELSON, the final assumption is that λ_G is approximately equal to λ_i, or more exactly that

$$[(\lambda\,\varkappa H)_G - (\lambda\,\varkappa H)_i] \simeq \lambda_i\,[(\varkappa H)_G - (\varkappa H)_i]$$

The error is a maximum when the driving force is a maximum but when $1/(\theta_G - \theta_i)$ is a minimum. Thus in the integrated expression for area:

$$A/G = 1/k_G \int di_G/(\theta_G - \theta_i) \quad \ldots (26)$$

the effect of the approximation is reduced and the number of transfer units (N.T.U.), i.e. $\int di_G/(\theta_G - \theta_i)$, will not be more than 2.5% low. The error will therefore lead to a conservative design, should such a small margin be of any consequence.

3. A Design Method for Cooler-condensers

The integral $\int di_G/(\theta_G - \theta_i)$ may be evaluated by determining $(\theta_G - \theta_i)$ at equal increments of di_G and summing the reciprocal values $1/(\theta_G - \theta_i)$. This usually results in half the area of the unit being accounted for by less than two out of ten of the increments[9] and a more accurate assessment of the N.T.U. is obtained by taking equal increments of gas temperature and summing $(di_G/dt)/(\theta_G - \theta_i)$. For this purpose, values of di_G/dt, termed by SILVER[9] the total heat capacity, have been calculated from Equation (8) and included in Table I together with other necessary properties such as enthalpy (i), humidity (H), enthalpy potential (θ), humid heat (S), the correction factor ($\varkappa$) and the rate of change of humidity and enthalpy potential with temperature (dH/dt and m_o).

When gas is cooled and dehumidified by direct contact with the cooling water, as in a packed tower, there is justification for ignoring the liquid film resistance and t_i may be taken as being t_L. If as is usually the case in gasworks practice, the gas is saturated entering the cooler-condenser, then i_G may be obtained from t_G and t_L is obtained by heat balance. The driving force $(\theta_G - \theta_L)$ is given by the difference in θ values at t_G and t_L and by reading off the value of di/dt the expression $dt \times \int \frac{(di_G/dt)}{\theta_G - \theta_L}$ may be evaluated by Simpson's rule. Provided the volumetric flow G is known, the N.T.U. so obtained may be used to calculate the mass transfer coefficient k_G for a specific cooler-condenser of area A; or for design purposes, calculated or experimental values of k_G may be employed to estimate the area of a proposed unit.

If the cooling operation is carried out indirectly such as in a tube and shell unit, the resistance on the water side may be appreciable, especially at the hot end. In order to determine the true driving force $(\theta_G - \theta_i)$, the interface condition must be known and this requires either a graphical construction, or a trial and error calculation. The graphical construction is based on Equation (25), from which is obtained the equation for the slope of a tie line:

$$(\theta_G - \theta_i)/(t_L - t_i) = -h_L/k_G \quad \ldots (27)$$

On a plot of θ vs. t a line drawn from a point on the operating line (θ_G, t_L) with a slope of $-h_L/k_G$ will intersect the saturation line at point (θ_i, t_i).

Alternatively, a value of t_i may be selected by trial and error such that Equation (27) is satisfied. These two methods require that both k_G and h_L be known, as, for example, in a design calculation. In the analysis of performance data, k_G is the unknown, a value of h_L being assumed from the generalised correlation of heat transfer to water flowing in tubes, i.e.:

$$h_L = 150\,(1 + 0.011\,t_L)\,V^{0.8}/d^{0.2} \quad \ldots (28)$$

A practical check on Equation (28) may be carried out by condensing steam on the shell side of the cooler-condenser. The solution to this problem is obtained by assuming a value of k_G, constructing the tie-line slopes, evaluating the N.T.U. and checking whether the value of k_G obtained agrees with the assumed value. Thus either a combination of trial and error calculation and graphical construction is involved, or one trial and error procedure is imposed upon another. In each case the method is protracted, but this feature is common to all the design methods for simultaneous heat and mass transfer except one. It is possible by adapting Silver's "sensible heat" method[9] to eliminate trial and error completely from an analytical procedure. The method is based on the assumption that the ratio of sensible heat to total heat transfer coefficients (R) is equal to the ratio of sensible heat to total heat capacity $[S/(di_G/dt)]$. The physical interpretation of this is that the heat and mass transfer rates are such that the gas remains just saturated as it passes through the unit. Equations (4) and (25) express the rates of sensible and total heat transfer respectively. If, however, it is assumed that enthalpy difference is the correct driving force, implying humidity driving force and a Lewis Number of unity, then:

$$-Gdi_G = k_G\,(i_G - i_i)\,dA \quad \ldots (29)$$

$$\text{or } -Gdi_G = k_G m'\,(t_G - t_i)\,dA \quad \ldots (30)$$

where m' is the slope of the chord $(i_G - i_i)/(t_G - t_i)$.

Thus the ratio of the transfer coefficients is $k_G m'/h_G$ or m'/S, since $h_G/k_G S$ is unity. This compares with the ratio of the heat capacities $(di_G/dt)/S$, the difference being that di_G/dt is the slope of a tangent to the saturation line at t_G while m' is the slope of the chord between t_G and t_i. The assumption upon which the method is based would therefore be a fair approximation if enthalpy were the correct potential for total heat transfer.

This assumption, at the higher temperatures, leads to driving forces which are too large and consequently transfer coefficients which are too small, as was observed by SILVER.[9] The heat capacity ratio concept does, however, suggest a means by which the graphical construction and most of the trial and error calculation can be eliminated from the enthalpy transfer potential method.

SILVER's method is developed from the FOURIER equation.

$$dQ = U\,(t_G - t_L)\,dA \qquad \ldots (31)$$

$$\text{or } dQ = h_G\,(t_G - t_i)\,dA/R = h_L\,(t_i - t_L)\,dA \qquad \ldots (32)$$

By rearrangement:

$$dA = \frac{R}{h_G}\,\frac{dQ}{(t_G - t_L)} + \frac{1}{h_L}\,\frac{dQ}{(t_G - t_L)} \qquad \ldots (33)$$

R is a unique function of the saturation temperature t_G and if A and h_L are known, h_G may be obtained by evaluating the integrals $\int RdQ/(t_G - t_L)$ and $\int dQ\,(t_G - t_L)$.

Similarly, the equation for total heat transfer in terms of the mass transfer coefficient k_G may be written:

$$1/K_G \int \frac{di_G}{(\theta_G - \theta_L)} = \frac{A}{G} = \frac{1}{k_G} \int \frac{di_G}{(\theta_G - \theta_L)} \quad \int \frac{m}{h_L}\,\frac{di_G}{(\theta_G - \theta_L)} \qquad \ldots (34)$$

where m is the slope of a chord on the enthalpy transfer potential saturation line $(\theta_i - \theta_L)/(t_i - t_L)$. Unlike R, m is not a unique function of the water temperature, but is dependent also on t_i. As a first approximation, however, m can be taken as m_o, the slope of the tangent $d\theta/dt$ at t_L, which is solely dependent on the water temperature, t_L. The relationship between m and m_o for various temperature gradients across the liquid film is shown in Fig. 2. The ratio m/m_o is plotted against t_i for convenience.

The steps in the modified method for analysing cooler-condenser performance are as follows:

(1) Divide the gas temperature into ten equal increments dt.
(2) Write down the values of i_G, (di_G/dt) and θ_G corresponding to t_G.
(3) From i_G determine the values t_L by heat balance.
(4) Write down the values of θ_L, m_o and h_L from t_L (Equation (28)).
(5) Evaluate $\int(di_G/dt)/(\theta_G - \theta_L)$ by SIMPSON'S rule and multiply by dt.
(6) Determine the ratio A/G.
(7) From steps 6 and 7, determine the value of K_G using Equation (34).
(8) Obtain $(t_i - t_L)$ from the relationship $K_G\,(\theta_G - \theta_L) = h_L\,(t_i - t_L)$.
(9) Use $(t_i - t_L)$ to write down value of m/m_o.
(10) Calculate the value of m.
(11) Evaluate the integral $dt[m\,(di_G/dt)/h_L\,(\theta_G - \theta_L)]$.
(12) Subtract this integral from A/G and determine k_G.

As an illustration of the method, Example 2, in the paper by SILVER,[9] has been selected and set down in detail in Table II, which is a copy of a form used for performance test data. The value of the coefficient k_G is equivalent to 89 ft/hr, which is of the order to be expected for a humidifi-

TABLE II

Date
Series No.: Reference 9
Test No. Example 2

Gas rate (G): 143 S.G.V./hr
Gas velocity: — ft/sec
Area: 10,130 sq. ft

Gas Inlet Temp.: 181°F
Gas Outlet Temp.: 62.6°F
$\frac{A}{G}$: 71.0

Water rate: 15,130 gal/hr
Water velocity: — ft/sec

	t_G	t_L	i_G	θ_G	θ_L	$\theta_G - \theta_L$	$\frac{di_G}{dt}$	$\frac{di_G}{dt(\theta_G - \theta_L)}$	m_o	$t_i - t_L$	t_i	$\frac{m}{m_o}$	m	h_L	$\frac{m}{h_L}\,\frac{di_G}{dt(\theta_G - \theta_L)}$
1	181.0	111.2	61,700	39,360	7,100	32,260	2775	0.08601	167	32.9	144.1	1.48	247	76.9	0.276
2	169.1	89.0	38,360	28,390	4,142	24,248	1403	0.05787	106	26.6	115.6	1.33	140	71.4	0.113
3	157.2	77.1	25,490	20,940	3,021	17,919	826	0.04610	83.7	21.1	98.2	1.23	103	66.7	0.071
4	145.4	69.6	17,660	15,710	2,429	13,281	527	0.03968	73.2	16.7	86.3	1.17	85.6	62.5	0.054
5	133.6	64.7	12,510	11,940	2,084	9,856	356	0.03612	67.8	12.4	77.1	1.11	75.3	60.0	0.045
6	121.7	61.5	8,970	9,070	1,872	7,198	249	0.03462	64.5	9.6	71.1	1.09	70.3	58.6	0.041
7	109.9	59.1	6,470	6,890	1,719	5,171	178	0.03438	62.1	6.9	66.0	1.06	65.8	57.2	0.040
8	98.1	57.4	4,690	5,198	1,615	3,583	130.4	0.03639	60.4	5.1	62.5	1.05	63.4	55.8	0.041
9	86.2	56.2	3,340	3,854	1,543	2,311	96.5	0.04176	59.3	3.3	59.5	1.05	62.3	54.4	0.048
10	74.4	55.2	2,360	2,799	1,484	1,315	72.5	0.05513	58.4	2.0	57.2	1.02	59.6	53.0	0.062
11	62.6	54.5	1,608	1,944	1,443	501	56.1	0.1120	57.8	0.8	55.3	1.00	57.8	52.6	0.123
Diff.	118.4	56.7	60,092												

$$\sum \frac{di_G}{\theta_G - \theta_L} = 0.4695 \times 11.84 = 5.559 \qquad \sum \frac{m}{h_L}\,\frac{di_G}{\theta_G - \theta_L} = 0.684 \times 11.84 = 8.1$$

$$K_G = \frac{5.559}{71} = 0.0783 \qquad h_G = 2.86$$

$$k_G = \frac{5.559}{71 - 8.1} = 0.0884 = 88.4 \text{ ft/hr}$$

TABLE III—Independent Determination of N.T.U. Required for Heat Transfer and for Mass Transfer

1. Gas temperature t_G	190	180	170	160	150	140	130	120	110	100	90	80	70
2. Gas enthalpy $\times 10^{-2} i_G$	97.30	59.15	39.63	27.94	20.30	15.06	11.31	8.56	6.49	4.94	3.73	2.79	2.06
3. Water temperature t_L	135.0	107.0	92.6	84.0	78.41	74.5	71.8	69.8	68.2	67.1	66.2	65.5	65.0
4. $(\alpha H)_G$	47.68	33.74	24.75	18.34	13.63	10.23	7.67	5.73	4.25	3.13	2.28	1.64	1.17
5. $(\alpha H)_L$	8.84	3.88	2.47	1.87	1.55	1.36	1.24	1.16	1.10	1.06	1.02	1.00	0.98
6. $\Delta\alpha H$	38.84	29.86	22.28	16.47	12.08	8.87	6.43	4.57	3.15	2.07	1.26	0.64	0.19
7. $a = c_p\,(\Delta\alpha H)/E$	0.541	0.416	0.310	0.229	0.168	0.124	0.090	0.064	0.044	0.029	0.0176	0.0089	0.0027
8. $e^a - 1$	0.718	0.516	0.363	0.257	0.183	0.132	0.094	0.066	0.045	0.029	0.0177	0.0090	0.0027
9. $t_G - t_L$	55.0	73.0	77.4	76.0	71.6	65.5	58.2	50.2	41.8	32.9	23.8	14.5	5.0
10. $c_p(t_G - t_L)/(e^a - 1)$	34.47	63.66	95.95	133.1	176.1	223.3	280.1	344	419	507	605	728	849
11. S	56.90	42.14	34.58	30.08	27.15	25.16	23.76	22.74	21.99	21.46	21.05	20.75	20.53
12. λ_G	984	990	996	1002	1008	1014	1020	1026	1032	1037	1043	1049	1054
13. $(dH/dt)_G$	4.83	2.23	1.268	0.792	0.532	0.369	0.264	0.192	0.141	0.103	0.077	0.057	0.040
14. $(dh/dt)_G$	0.1076	0.095	0.080	0.066	0.056	0.046	0.039	0.032	0.026	0.020	0.0155	0.0117	0.0071
15. $(dH/dt - dh/dt)_G$	4.72	2.14	1.19	0.726	0.476	0.323	0.225	0.160	0.115	0.083	0.0615	0.0453	0.0329
16. $(dH/dt - dh/dt)_G/(\Delta\alpha H)$	0.122	0.072	0.053	0.044	0.039	0.036	0.035	0.035	0.037	0.040	0.049	0.071	0. 173
17. $S + \lambda_G(dH/dt)_G$	163	136	114	96.6	83.8	72.1	63.1	55.2	48.4	42.1	37.2	33.0	28.0
18. $a/(e^a - 1)$	0.754	0.806	0.854	0.891	0.919	0.940	0.959	0.970	0.979	0.985	0.991	0.995	0.999
19. $h_G\,(dA/dt)_G$	3.93	2.31	1.73	1.43	1.27	1.17	1.13	1.13	1.18	1.30	1.58	2.29	5.60
20. $(di/dt)_G$	5597	2590	1478	928	628	441	317	237	178	136	106	82.4	66.0
21. $\theta_G \times 10^{-3}$	52.03	38.19	29.07	22.47	17.53	13.84	10.97	8.730	6.910	5.444	4.249	3.271	2.459
22. $\theta_L \times 10^{-3}$	12.33	6.44	4.54	3.64	3.13	2.80	2.60	2.444	2.327	2.249	2.186	2.138	2104
23. $(\theta_G - \theta_L) \times 10^{-3}$	39.70	31.75	24.53	18.83	14.40	11.04	8.37	6.286	4.583	3.195	2.063	1.133	0.355
24. $(di/dt)_G/(\theta_G - \theta_L)$	0.1410	0.0816	0.0602	0.0493	0.0436	0.0400	0.0379	0.0378	0.0389	0.0427	0.0515	0.0727	0.1859

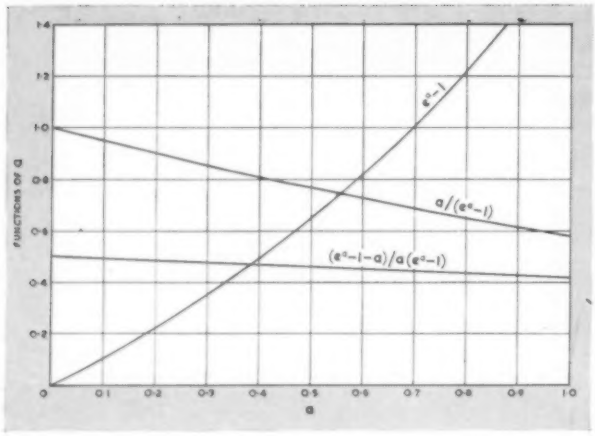

Fig. 1. Exponential functions required when allowing for the rate of sensible heat transfer accompanying diffusion.

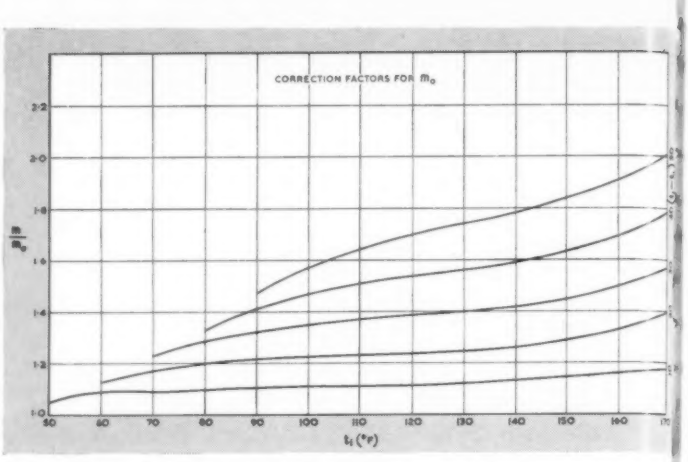

Fig. 2. Factors relating the chord slope $(\theta_2 - \theta_2)/(t_1 - t_L)$ to the tangent slope $d\theta/dt$.

cation process. The equivalent sensible heat transfer coefficient is 2.86 Btu/ft² hr °F, which is considerably higher than the value of 1.2 Btu/ft² hr °F obtained by SILVER. The liquid film resistance in this example is just over 11%, i.e.,

$$\int \frac{m\, d_{iG}}{h_L(\theta_G - \theta_L)} \text{ compared with } A/G.$$

It is appreciated that k_G is not a constant and theoretically it should increase with temperature, especially above 140°F. There are not at present sufficient data to make a specific allowance for this variation in the design method, so average values of k_G are determined.

4. Fog Formation in Cooler-condensers

As has been stated previously, the Lewis Number for the water vapour-coal gas system is greater than unity and this, combined with the fact that the driving force for mass transfer is less than the humidity difference, means that the heat transfer to mass transfer ratio is greater than that required to maintain the gas in a condition where it is just saturated and water vapour condenses in the main body of the gas. This is known as "fog formation" and may be expressed mathematically by the relationship:

$$(dH/dt)_G > \frac{k_G[(\varkappa H)_G - (\varkappa H)_i]}{h_G(t_G - t_i)/S}$$

If it is assumed that the rate of fog formation with temperature is $(dh/dt)_G$, then the above inequality may be written as an equation:

$$[(dH - dh)/dt]_G = \left(\frac{k_G S}{h_G}\right)\left[\frac{(\varkappa H)_G - (\varkappa H)_i}{(t_G - t_i)}\right] \quad \ldots.(35)$$

The first group on the R.H.S. of Equation (35) is a function of the system and is the reciprocal of the Lewis Number; the second group is a function of the operating conditions.

Due to the high latent heat of water, the quantity of fog formed is a small fraction of the total water condensed. For example, gas in cooling along the saturation line from 180°F to 70°F loses 48 lb/S.G.V. of water and 2790 Btu/S.G.V. of sensible heat. If the net ratio of sensible heat to mass transfer over this range were twice that required to maintain saturation, then approximately 2.8 lb/S.G.V. of water would appear as fog or about 6% of the total condensed. Thus although the percentage of condensed water which appears as fog may be small, assumptions as to the relative rates of heat and mass transfer on the basis of no fog formation are not justified. Furthermore, if in the example quoted, all the fog was carried forward with the gas stream, the effect would be quite serious if the intention were to dehumidify the gas, since the additional 2.8 lb/(S.G.V.) of water would give a dewpoint of 107°F as opposed to 70°F.

T. MIZUSHINA[10] proposed that in the case of high humidity the method of COLBURN and HOUGEN[11] may be used to calculate the area required for total heat transfer. From the rate equation for mass transfer the rate of water vapour transfer at each step can be calculated. By integration the amount of water vapour transferred across the interface is then calculated and compared with the total quantity of water vapour condensed, obtained from the material balance equation. The difference between these two amounts of vapour condensed may be considered to be the amount of fog.

This technique is not applicable to the design method outlined in this paper, since many approximations have been made in its development and a 5% error in the estimation of the quantity of water vapour transferred would produce a considerable error in calculating the quantity of fog formed. Furthermore, the method takes no account of the additional sensible heat to be transferred due to water condensing in the bulk of the gas and the effect of the diffusing vapour on the sensible heat transfer coefficient h_G. Both these factors become significant when considering the relative rates of heat and mass transfer. Making allowance for the quantity dh of water vapour which appears as fog and for the sensible heat of the diffusing vapour, Equations (4) and (5) may be rewritten as follows:

$$-GSdt_G - G(dH - dh)_G\, c_v(t_G - t_i) - G\,(dh\,\lambda)_G = h_G(t_G - t_i)\left(\frac{a}{1 - e^{-a}}\right)DA \quad \ldots.(4a)$$

and $$-G(dH - dh)_G = k_G[(\varkappa H)_G - (\varkappa H)_i]\,dA \quad \ldots.(5a)$$

Using the relationship $a = -G\,(dH - dh)_G\, c_v/h_G\, dA$.

$$GSdt_G + G(dH - dh)_G\, c_v\,(t_G - t_i) + G(dh\,\lambda)_G = G(dH - dh)_G\, c_v\,(t_G - t_i)/(1 - e^{-a}) \quad \ldots.(4b)$$

Dividing through by G and collecting terms

$$Sdt_G + (dh\lambda)_G = (dH - dh)_G\, c_v(t_G - t_i)\,[(1 - 1 + e^{-a})/(1 - e^{-a})]$$

Thus $$dh_G\left[\lambda_G + \frac{c_v(t_G - t_i)}{(e^a - 1)}\right] = dH_G\left[\frac{c_v(t_G - t_i)}{(e^a - 1)} - Sdt_G\right]$$

or $$(dh/dt)_G = \left[\left(\frac{dH}{dt}\right)_G c_v\left(\frac{t_G - t_i}{e^a - 1}\right) - S\right] \Big/ \left[\lambda_G + c_v\left(\frac{t_G - t_i}{e^a - 1}\right)\right] \quad \ldots.(36)$$

This is the equation for determining the rate of fog

formation at each stage in cooler-condenser. Equation (36) may also be written as:

$$SGdt_G + G(dh\lambda)_G/ = h_G(t_G - t_i)\ [a/(1 - e^{-a}) - a]$$

From which

$$h_G dA/G = \frac{[S + \lambda_G (dh/dt)_G]\, dt_G}{[(t_G - t_i)\, [a/(e^a - 1)]} \quad \ldots . (37)$$

This equation enables the area of the cooler-condenser to be calculated in terms of the sensible heat transfer coefficient h_G, and the area so calculated should agree with that obtained by using Equation (5a).

To illustrate the method by which the amount of fog may be estimated, the heat and mass transfer taking place in a washer-cooler are considered separately. The duty of the unit is to cool gas from a saturation temperature of 190°F to 70°F, the circulating water rising in temperature from 65°F to 135°F. Since the gas and water are in direct contact, the liquid film resistance is assumed to be negligible; i.e., t_i is equal to t_L. The steps in the calculation are set down in Table III. Having subdivided the gas temperature range into an even number of increments, the corresponding water temperatures are determined by heat balance. The next step is write down the mass transfer driving force $\triangle_{\mathrm{a}}H$ and hence evaluate the term a equal to $c_v \triangle_{\mathrm{a}}H/E$. Fig. 1 and Table I then provide the values required for substitution in Equation (36) with the exception of λ_G, which may be obtained from steam tables, and c_v, which is assumed to be 0.45 Btu/lb. The quantity of fog that could be formed, $\int dh_G$, is obtained by summing $(dh/dt)_G$ by Simpson's rule. The final value of 5.43 lb/S.G.V. compares with 80.9 lb/(S.G.V.), the difference in humidity between gas at the saturation temperatures of 190°F and 70°F respectively. The N.T.U. required for transferring the net quantity of water vapour condensed $\int (dH/dt - dh/dt)/(\triangle_{\mathrm{a}}H)$ is 6.38 units and this is equivalent to $k_G A$; $h_G dA/dt$ (line 19) is obtained from Equation (37) and the summation of the values gives $h_G A = 206$ Btu/S.G.V. °F. The ratio of the values h_G/k_G is 32.3 Btu/(S.G.V.) °F, which was the value initially assumed for E; thus the areas required for mass and sensible heat transfer are identical. Finally the N.T.U. for total heat transfer by the method described is found to be 6.96, an error of 9%. The quantity of fog formed is 5.43/80.9 or 6.7% of the total water condensed. This reduces the area required for mass transfer and the percentage reduction accounts for most of the discrepancy between the N.T.U. calculated from lines 16 and 24.

It is most unlikely that all the fog formed is carried out with the gas. The fog droplets tend to coalesce and fall out of the gas stream, and much is removed when droplets impinge on solid surfaces at changes of direction in the condenser. CRADDOCK[1] reports evidence of supersaturation in atmospheric condensers where the sensible heat transfer is aided by radiation, but no evidence of such in water tube condensers, where the gas is usually flowing over banks of tubes. Precipitation of moisture by passage of a fog-laden atmosphere round cylindrical obstructions is a well-known phenomenon. The branches of trees and telegraph wires perform this function in foggy weather.

It may not be possible therefore to detect the presence of fog at the outlet of such condensers, but it is not a valid assumption that heat and mass transfer proceed at rates which maintain the gas in a just saturated condition.

In order to confirm the formation of fog when cooling saturated gas, even in a narrow tube, a simple condenser was set up in the laboratory. Saturated gas was produced over a range of temperatures by bubbling town gas through hot water in a flask fitted with a 3-kW immersion heater. A simple Liebig condenser was mounted vertically above the flask and the temperatures of the gas entering and leaving the condenser were indicated by mercury-in-glass thermometers. The gas leaving the condenser passed through a glass tube wound with heating tapes sufficient to re-evaporate any moisture carried out as fog. Finally, a sample of the gas was passed to a dewcell instrument, which gives a direct indication of the dewpoint of the gas, irrespective of its temperature, provided this is within prescribed limits. The supply of cooling water to the condenser was such as to provide negligible resistance to heat transfer on the water side.

The difference in humidity of the gas between the indicated dewpoint and the temperature at which it leaves the condenser is a measure of the excess water present either as fog or in the vapour phase if the gas is supersaturated. This quantity is best expressed as a percentage of the humidity difference between the inlet and outlet gas and it may be calculated from Table III (line 14 divided by line 13) that $\int (dh/dt)_G$ divided by $\int (dH/dt)_G$ over the range 70°F to 130°F is 17.7%. This is true only for the water temperature distribution assumed in Table III. If, for example, as in the laboratory experiments, the water is at a lower but uniform temperature of 50°F, the calculated percentage of condensate which could appear as fog increases to 22.9.

The highest percentage obtained in the laboratory experiments over the range 70°F to 130°F was 17.7, five other results being in the range 11 to 14%. These values are below that predicted, but there is no guarantee that all the fog formed reaches the outlet of the condenser tube. The fact that the results are not easily reproducible tends to confirm that it does not. Furthermore, the concentration of fog in the tube was observed to be greater in the lower half than in the upper half near the gas exit. If none of the fog droplets was removed from the gas stream in its passage through the condenser tube, then the concentration would be a maximum at the gas outlet. The laboratory experiments, therefore, do not disprove the data and equations upon which Table III is based, but they do clearly demonstrate that fog formation in the bulk gas stream is appreciable when town gas, initially saturated with water vapour, is cooled even in a narrow tube (approx. $\frac{1}{2}$-in. bore).

Although Equation (36) will not predict quantitatively the precise excess humidity at any point in the process, several useful qualitative facts may be deduced from it by rearrangement.

The group $c_v(t_G - t_i)/(e^a - 1)$ may be written as $f\, c_v(t_G - t_i)/a$ where f is the factor $a(e^a - 1)$ plotted in Fig. 1. Substituting for a, the expression simplifies to $fE\triangle t/\triangle(\triangle_{\mathrm{a}}H)$. The rate of fog formation is therefore dependent on the difference between the two terms $fE[(dH/dt)_G/(\triangle_{\mathrm{a}}H/\triangle t)]$ and S.

It will be observed from Table III that at the low temperature end both f and $(dH/dt)_G/\left(\frac{\Delta_{\mathrm{a}}H}{\Delta t}\right)$ approximate to unity and the principal cause of fog formation is the difference between E and S.

At the higher temperatures the ratio $(dH/dt)_G/[(\triangle_{\mathrm{a}}H)/\triangle t]$ increases rapidly, but this is offset by a corresponding decrease in f and increase in S, so that the percentage fog formation actually decreases. The E and S values listed in Table I were determined for a typical town gas made by conventional methods. If, however, the gas contains a high percentage of hydrocarbons the specific heat of the dry gas will be higher than 20 Btu/(S.G.V.) (°F) and this will reduce dh/dt, the effect being more pronounced at the lower temperatures. For the purposes of comparison, saturated air was passed through the laboratory condenser in place of the town gas under the same conditions of flow, inlet temperature and water temperature. The excess of dewpoint over outlet gas temperature was 2.6°F for air, compared with 9.3°F for town gas. This is in accordance with theory, since for the air and water system, the ratio of

transfer coefficients does approximate to the humid heat at ambient temperatures.

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53rd Annual Meeting of the A.I.Ch.E.

THE 168 papers presented at the recent 53rd Annual Meeting of the A.I.Ch.E., held in Washington, covered subjects ranging from the processing of propellents to optimisation studies. As is usual with these massive events, numerous social functions and trips to plants and research establishments were organised.

The papers were arranged in a number of symposia with the following titles: "Propellent Processing", "Fluid Dynamics", "Saline Water Conversion", "Automobile Exhaust After-burners", "Economic Evaluation of New Processes", "Chemical Engineering in the Mineral Industries", "Information and Communication", "Evaluation of Equipment Used for Air Pollution Control", "Solving Pollution Control Problems", "Heat Transfer", "Phase Transitions", "The Unsteady State as an Analysis Tool in Chemical Engineering", "Toxic Plant Construction", "The Role of the Chemical Engineer in Environmental Chemical Engineering", "Nuclear Chemical Plant Safety".

To single out papers for special mention from among this formidable array is difficult. However, in the saline water symposium a design of some interest was described by BROMLEY and CLARK. This is a 4-ft-diameter, 28-effect, rotating evaporator which was constructed and operated for producing distilled water. How to predict the performance of this evaporator under various operating conditions was one of the features of the paper.

Also in this group was a paper describing a method of converting saline water by direct contact with the refrigerant butane. This appears to be an attractive process because equipment first cost is low, and so too is the power consumption of 30 kWh per 1000 gallons of product water.

In the information group of papers, KNOX described recent steps taken by the Esso Research & Engineering Co. to make use of the technical literature. In this same field MORSE proposed the use of a concept co-ordination index system on the part of publishers which he considered will speed up the collecting of information. Messrs. TAYLOR and RASMUSSEN, who belong to the same company as MORSE, E. I. du Pont de Nemours & Co., dealt with the mechanised retrieval of technical information within a central engineering department.

Another du Pont paper appeared in the Economic Evaluation Symposium and was concerned with the use of computer simulation for new processes, especially where some element of financial risk is involved. A review of a method of evaluating petroleum processes, followed by a discussion of short cuts for approximate estimates, and for projection-type economics, is given by BARR in his paper. The techniques described are illustrated by reference to the cost of petroleum operations such as fluid coking and hydrofining.

The subject of heat transfer produced its usual rich crop of papers. Thus, HOUGEN appeared as part author of a paper dealing with partial pressure and temperature gradients from fixed-bed catalyst particles to ambient streams, based on literature data on reaction rates, and methods of evaluating these gradients. In a paper describing the effect of acoustic vibrations on forced convective heat transfer LEMLICH and HWU report considerable increases in Nusselt numbers for both the laminar and turbulent regions in the presence of vibrations of air and they present correlations which embrace their experimental results.

GORDON, in a paper devoted to mass and heat transfer in packed beds, makes use of a mixing stage model and the surface renewal theory to relate the "j" factor for packed beds with Reynolds number. The equations derived show good agreement with reported data for particles greater than 4 mm in diameter.

A number of sophisticated papers were given in the symposium "The Unsteady State as an Analytical Tool". PUCKETT and others dealt with the determination of the frequency response characteristics by correlation techniques using a continuous stirred tank as the process; an aim of this study was to evaluate some accuracies and limitations of such techniques. The feasibility of pulse testing, is discussed by HOUGEN and WALSH as a method of obtaining process dynamics. OTTO and STOUT use the statistical properties of the time-response of a system disturbed by an arbitrary pulse, for describing the dynamics of process equipment, a method which they apply to an agitated vessel. LAPIDUS deals with some of the more important methods of analysing chemical reactor data for determining kinetic mechanisms. In this paper a strong point is made on the use of computers for data reduction and manipulation.

Frequency response, step response and pulse response techniques were employed by STEWART, PUCKETT and SLIEPCEVICH to study the dynamic heat removal from a jacketed agitated vessel.

In the symposia dealing with pollution, one paper (KIELBACK) describes how a pollution problem in an aluminium plant was solved by the use of floating-bed scrubbers. In the same symposium GILBERT discusses the operating costs for fourteen different types of collector, including wet collectors, dry and irrigated cyclones, electrostatic precipitators and fabric filters. It is shown that the cost of removing dust is determined more by the required efficiency of dust removal than by the type of collector.

The paradox concerning the relation between the drag on a small spherical particle and the pressure drop arising from its presence in an infinitely wide cylindrical tube through which a fluid is flowing is resolved by BRENNER in his theory of low-Reynold-no. fluid particle systems.

SLEICHER, who spent a period recently at Cambridge in this country, examines the maximum stable drop size in turbulent flow of two immiscible liquids. He shows that the drop size varies much more strongly with velocity and interfacial tension than had previously been supposed. A correlation is presented which can be used for the design of pipeline reactors.

Finally, mention should be made of a paper by HOMME and OTHMER who, in the symposium allocated to special papers, show how a complete sulphuric acid plant operation could be simulated in order to determine its most profitable mode of operation for any given catalyst and for any values of the uncontrollable variables.

66.067.34

A rotary drum filter filtering ferrous sulphate monohydrate in 50% sulphuric acid. (Photograph by courtesy of the I.C.I. Ltd. Billingham Division.)

THE EFFICIENCY OF CONTINUOUS ROTARY DRUM FILTRATION

A new approach for analysis of continuous filtration is presented based on examination of relative pressure drop across the filter medium and across the cake. Treatment of data indicates the optimum filter media, or most efficient filtration, to obtain a separation in cake filtration

by HARRISON R. COOPER*

1. Introduction

PROCEDURES for calculating filtration rates are still unsatisfactory because there have been no methods available for conveniently evaluating filter media resistance to predict performance under operating conditions. In continuous filtration, filter media resistance can be compared to heat and mass transfer coefficients inasmuch as rate constant data for these processes are all obtained as empirical quantities. A method for treatment of continuous drum filtration data is presented which permits extracting filter media performance coefficients. This method is derived by algebraic manipulation of the fundamental filtration equation, stemming from previous work by MONDRIA.[6]

Very little fundamental understanding has been achieved to describe the processes which take place at the filter media during the course of filtration. Experimental investigation of filtration processes has resulted in developing useful knowledge concerning the behaviour of resistance properties of the solids, but the field of application of this knowledge is limited because solids resistance data have not been rationally treated with concomitant media flow resistance. The mechanics of interaction of filtered solids with the filter media, causing changes in the media, are not fully understood. Design of continuous filtration equipment is dependent on the performance and hydraulic resistance of filter media since the media pressure drop can be up to 50% of the total pressure drop across the filter. In view of the lack of theoretical understanding, it is of interest to develop performance data by examination of filter media properties by a purely empirical process. Filtration performance data can be used to obtain empirical coefficients for filtration rates to which corelation procedures could be applied.

2. The Filtration Process

The process of filtration depends on interception of solid particles from a slurry in porous material or on filter media. The rate of filtration is governed by hydraulic resistance of the filter media and solids accumulating in the cake. Mathematical expressions developed for interpretation of filtration rates have usually attributed resistance to filtrate flow to two mechanisms: resistance of the solid cakes which form on the filter surface, and resistance of the filter media. The procedure for laboratory evaluation of resistance properties for cake solids has recently been developed to a high degree of proficiency by means of compression-permeability cell analysis.[2, 4, 5] Investigators have also studied characteristics of filter media and have reported comprehensive data on structural formation, sizes of pores, and manner of fabrication with the intention to relate these factors to resistance properties of media determined from experimental data.[3] Useful facts have been brought out by these studies, especially for the mechanisms of media filtration, when no cake is formed, up to the point of incipient cake formation. But for the process of cake filtration, which is the case being considered, almost no generalisations have been made.

The conventional constant pressure filtration lends itself to the analysis of data for determination of specific resistance of cake solids and, by extrapolation, to the calculation of medium resistance.[8] It has been frequently observed that filter media resistance values obtained by reducing constant pressure filtration data indicate great discrepancies between original media properties and calculated values. Clean media have flow resistances as low as 1/1000 of calculated media resistance values taken from constant pressure filtration data. Accuracy in determining experimental media resistance from constant pressure filtration data is difficult to achieve because small measurement errors during the first

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Symbols Used

A = area, sq ft;
D = diameter, ft;
g_c = proportionality constant relating force and mass, 32.2 ft lb mass/(lb force) (sec^2);
h = height of fluid column, ft;
h_{av} = average of fluid column, ft;
k, K = constant term denoting combination of several constants grouped for convenience as indicated;
m = mass ratio of wet cake to dry cake, dimensionless;
p = pressure, lb force/sq ft, unless noted as given in units lb force/sq. in. (with prime symbol, indicates p corrected for static head);
p_0 = nominal filtration pressure as in vacuum filtration, units as in p;
p_1 = hydraulic pressure at filter medium cake interface, units as given in p;
p_h = pressure added to p to correct for static head, units same as p;
q = flow rate per unit area of filter cake or superficial velocity of flow through cake, cu ft/(sq ft) (sec);
R = radius of filter drum, ft;
R_m = medium resistance, 1/ft;
s = weight fraction solids in slurry, dimensionless;
t = time of one cycle of filtration, seconds or minutes as indicated;
v = volume of filtrate per sq. ft, cu ft/sq ft;
V = volume of filtrate per sq ft averaged per unit time, cu ft/(sq ft) (sec);
w = solids deposited in filter cake per unit area, lb mass/sq ft;
x = dimensionless ratio, ω/ω_{ref};
y = dimensionless ratio, V/V_{ref};
α = specific resistance of deposited solids, ft/lb mass;
β = angle of submergence of drum filter, fraction of circumference;
μ = viscosity, lb mass/(ft) (sec);
ρ = density of filtrate, lb mass/cu ft;
ρ_f = density of slurry, lb mass/cu ft;
ρ_s = density of solids, lb mass/cu ft;
Φ = angle from axis of rotation in drum or disc filter subtending an arc on the periphery of the drum, fraction of circumference;
σ = dimensionless quantity, $\dfrac{\alpha k v}{R_m}$;
ω = rate of rotation of drum or disc filter, revolutions per minute or second (as indicated).

TABLE I—Reduced Copper Slurry Filtration Data

Run	1	3	4
ω, rpm	0.133	0.375	0.606
Cake form pressure, in. Hg	6	10	10
Filtrate rate, gpm	1.48	3.13	3.85
Wet cake discharge, lb/min	1.48	3.48	4.07
Dry cake discharge, lb/min	0.97	2.37	2.66
Slurry wt. %	6.2	7.2	6.6
Viscosity, cp	0.67	0.67	0.67
σ		7.38	6.12
α, ft/lb$_m$		1.44	(10^{10})
R_m 1/ft		2.95	(10^9)
E	0.83	0.79	0.75

Filter: Dorr-Oliver 36 in. diameter by 6 in. cake width submerged to 55% of the surface.

TABLE II—Ruth-Kempe Filtration Data (November 19, 1934)

Run	Min/Rev	Min/Litre
1	1.96	0.564
2	5.14	0.687
3	9.59	0.848
4	22.10	1.111
5	23.67	1.245
6	7.21	0.822
7	94.2	2.13
8	9.18	0.880
9	2.96	0.596
10	1.94	0.537

portion of experimental runs are very significant in calculating media resistance. This procedure is also deficient in that there is no assurance that media resistance is the same at the instant that the filtration run begins as it is at the end of the filtration. It may be stated in general that performance of filter media is a complex function of solids properties,† operating conditions or pressure, and structural properties of the media. Discussion has been presented which introduces phenomena such as boundary layer behaviour, electrokinetic effects, surface pore blocking due to particle migration, etc., to explain experimental observations in cake filtration in which consideration of filter media behaviour is often neglected. The significance of these phenomena as yet has not been described mathematically and recourse must continue to be made to expensive performance tests to estimate design requirements.

3. Continuous Drum Filtration

Continuous filtration by the rotary drum process is performed by repeated immersion of each segment of filter surface on the revolving drum periphery. At a point on each rotation cycle, the solid cake is removed to obtain fresh surface which re-enters the slurry to pick more cake. Steady-state operation is achieved when the quantity of solids on a segment of drum at a given point in the slurry is a constant.

In ideal steady state filtration, the problem of determining filter media resistance is greatly simplified, since an equilibrium condition of slurry input and cake output with time is indicative that media resistance has reached a constant value at constant drum rotation. Extracting media resistance values from continuous filtration data eliminates the experimental drawbacks which are present in analysis by means of constant pressure filtration. Ideal steady-state filtration represents a process in which the medium resistance does not change with time. Practical conditions are something less than this, since during cake filtration a medium is subject to mechanical and chemical degradation. The medium gradually becomes less operable or less efficient as its time in operation increases.

The differential equation for continuous drum filtration is usually stated for one cycle of drum rotation at a rate ω revolutions per sec:

$$q = \omega \frac{dv}{d\Phi} = \frac{g_c (1 - ms)}{v \mu s \rho} \int_0^p \frac{dp}{\alpha} \qquad \ldots . (1)$$

Fig. 1 shows the schematic outline of a drum filter. Integration from $v = 0$ to v, and $\Phi = 0$ to β permits calculation of the volume of filtrate obtained in one filtration cycle. The general equation for superficial flow rate at any point in the thickness of a compressible filter cake for finite pressure difference between cake surface and cake media interface has been written in terms of mass of cake solids, porosity, and (empirically determined) point specific resistance α. Equation (1) is a good approximation when the superficial velocity of filtrate flow, q, can be considered constant in the cake thickness, which holds when volume ratio of solids to liquid in the slurry is 0.05 or less.[10]

The pressure, p, is pressure differential between the drum surface and cake-medium interface. In rigorous analysis, p is a variable in Φ, since the pressure at the drum surface is the sum of the submergence head and operating pressure less the pressure drop across the medium. Taking the drum interior pressure as the datum, p is expressed:

$$p = p_0 + p_h - p_1 \qquad \ldots . (2)$$

† Solids properties resulting from environment liquid properties such as viscosity, surface tension, impurities, ionic activity, etc., are considered to be inseparable from those specific to the solid itself.

NOTE: The nomenclature used here conform to that agreed upon at a meeting of F. M. Tiller, H. P. Grace, B. F. Ruth, C. D. Luke, R. L. Ingmanson, C. D. Ulrich, and others at the Cleveland meeting of the A.I.Ch.E., December 1952.

Specific resistance α is, in general, a function of solids pressure, p, when compressible solids are filtered. In Equation (2) p_0 is the vacuum pump differential assuming negligible line friction loss, p_h is the static head contribution, and p_1 is the hydraulic pressure at the cake medium interface.

4. Analysis of Continuous Drum Filtration Data

Computations can be performed for rotary drum filtration using Equation (1) in integrated form if two simplifications are made. First, that an average correction can be added to p_0 for static head; and, second, that α is constant. It has been demonstrated in rigorous computation that the error is very small when filtrate volumes are calculated by numerical integration considering variable p and α and volumes calculated using an integrated α from compression-permeability cell measurement at $p_0 + p_h$, the integrated average static head correction p_h being calculated by the expression[1]

$$p_h = \frac{2}{\beta} Rp_f \left[\sin\left(\frac{\beta}{2}\right) - \left(\frac{\beta}{2}\right)\cos\left(\frac{\beta}{2}\right)\right] \qquad \ldots . (3)$$

Assumption of constant α for rotary drum filtration calculations is further justified by the fact that most experimental evidence indicates that equilibrium compression of solids is attained after 15 min or more following stress application. A cycle of filtration with a rotary drum filter is rarely greater than 3 min, precluding the equilibrium consolidation of solids. Integration is possible using these assumptions, and Equation (1) then becomes:

$$q = \omega \frac{dv}{d\Phi} = \frac{g_c (1 - ms)}{\mu\, v\, s\rho} \frac{p_0 + p_h - p_1}{\alpha} = \frac{g_c (1 - ms)}{\mu\, v\, s\rho} \frac{p' - p_1}{\alpha} \qquad \ldots . (4)$$

The solid cake-medium interface pressure, p_1, is conventionally defined by an equation similar to Equation (1), assuming that a resistance constant exists such that the hydraulic pressure loss can be described by the relation:

$$p_1 = \frac{\mu}{g_c} q\, R_m \qquad \ldots . (5)$$

where R_m is a medium resistance factor to be empirically determined. Substitution of Equation (5) in Equation (1) for p_1 permits integration with the result

$$\frac{\alpha\,\omega}{2} \frac{\mu}{g_c} \frac{s\rho}{1 - ms} v^2 + R_m \frac{\mu\omega}{g_c} v = (p_0 + p_h)\,\beta \qquad (6)$$

The term R_m may not be specific to the medium itself as previous investigators have noted. Hydraulic resistance of filter media is in general influenced by the solid material in the slurry as much as by the media structure. In addition, the pressure of the system is suspected of being a contributing factor to the value of filter media resistance, particularly when solids are compressible (specific resistance increases with pressure).

Since the variables α and R_m in Equation (6) are both functions of system properties, to solve for numerical values of α and R_m in a given rotary filtration process, data for constant slurry, medium and pressure at two speeds of rotation are needed. MONDRIA has developed a convenient form for solving Equation (6) simultaneously with the two sets of data required.‡[6]

$$\sigma y^2 + 2xy - x(\sigma + 2) = 0 \qquad \ldots . (7)$$

with the dimensionless quantities σ, x and y for the two data sets (denoted a and b) defined as follows:

$$\sigma = \frac{k\,\alpha\, v}{R_m} = \frac{k\,\alpha\, V}{R_m\,\omega}$$

$$x = \frac{\omega_b}{\omega_a}$$

$$y = \frac{V_b}{V_a}$$

In the equation for σ, the steady-state rate of filtrate production is

$$V = \frac{\text{volume per cycle}}{\text{time per cycle}} = \frac{v}{t} = v\omega$$

The term σ obtained by treatment of data according to Equation (7) thus contains two unknowns, α and R_m. It is assumed that α and R_m are system constants (no difference in compressibility effects between the two runs) in treating two sets of data. If data are available for several rates of rotation, the data can be calculated successively with one set as reference for statistical treatment as illustrated in Example 2. Rearrangement of Equation (6) and substitution of the definition of σ enables direct solution for values of α by the expression

$$\alpha = \frac{2\,p'\,\beta}{\omega \frac{\mu}{g_c} k\, v^2 \left[1 + \frac{2}{\sigma}\right]} \qquad \ldots . (8)$$

where p' is the filtration pressure corrected for static head, if significant. In a practical filtration problem, such as selection of the optimum filter medium, a factor of immediate concern is the availability of pressure driving force for filtration. The greatest filtration driving force will be provided by the medium with the highest efficiency, that is, the least resistance. Whereas under steady-state conditions, the filtrate production rate is ideally constant, the filter medium-cake interface hydraulic pressure, p_1, changes constantly because of cyclic cake build-up and removal. A more convenient means is desirable for evaluating performance

‡ Derivation of this equation is demonstrated in Appendix I.

TABLE III—Analysis of Ruth-Kempe Filtration Data

		Reference Run 1	2	3	4	5	6	7	8	9	10
Calculated σ	1		1.02	1.87	2.95	4.01	2.18	7.9	2.34	0.47	−1.15*
	2	0.47		2.58	3.15	5.66	−18.2*	8.8	6.84*	0.84	0.72
	3	0.58	2.59		2.44	7.05	0.26	8.4	−0.54	0.99	0.74
	4	0.54	1.20	1.38		1.93*	0.79	13.7*	0.84	0.81	0.62
	5	0.75	2.21	4.39	14.7*		1.84	8.3	2.08	1.16	0.91
	6	0.88	16.2*	0.32	1.71	3.34		6.5	1.45	1.94	1.19
	7	0.62	1.51	2.17	6.11*	2.35	1.32		1.56	0.95	0.72
	8	0.79	4.90*	−0.66	1.55	3.58	1.25	6.6		1.53	1.02
	9	0.32	1.26	5.32	3.23	4.74	3.45	8.6	3.13		0.85
	10	−0.09	1.46*	2.33	3.42	4.67	2.86	8.8	2.92	1.12	
$1/\omega$ (min)		2.0	5.1	9.6	22.1	23.7	7.2	94.2	9.2	3.0	1.9
σ		0.50	2.06	2.19	2.98	3.79	1.42	9.5	2.36	1.09	0.69
$\sigma_{0.95}$		0.61	1.61	2.19	2.64	4.42	1.74	8.0	1.72	1.09	0.85
$s_{\sigma\text{-}95}$		0.196	0.49	2.00	0.69	1.62	1.11	0.80	1.29	0.495	0.165
$E_{\sigma\text{-}95}$		0.23	0.44	0.52	0.57	0.69	0.46	0.80	0.46	0.35	0.30
$K\frac{(\alpha)}{R}$		0.17	0.21	0.19	0.13	0.23	0.20	0.18	0.16	0.22	0.24

* Values eliminated by statistical analysis for 95% confidence limits. The subscript 0.95 indicated in the first column of the bottom half of the table denotes results of calculations using the values within 95% confidence limits.

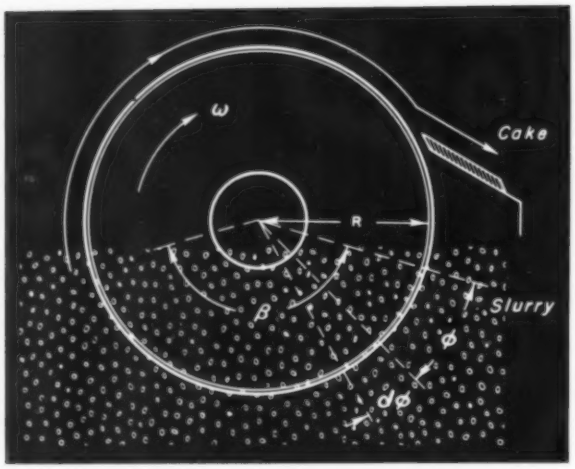

Fig. 1. Nomenclature used in the analysis of the efficiency of rotary drum filtration.

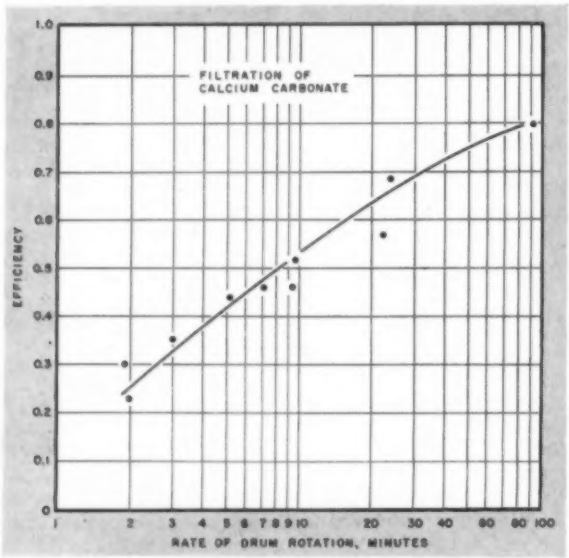

Fig. 2. Filtration efficiency vs. rate of drum rotation (Ruth-Kempe data).

of filter media which avoids the necessity of direct examination of interfacial hydraulic pressure. A new coefficient, filtration efficiency, will be defined in accordance with this approach by the expression

$$E = \frac{p' - p_1}{p'} \qquad \ldots\ldots(9)$$

Combining Equations (6) and (8) results in the simple expression§

$$E = \frac{\sigma}{\sigma + 2} \qquad \ldots\ldots(10)$$

Use of the coefficient E to compare filtration capability of media under different conditions offers the advantage that no consideration need be given to numerical values of media resistance, which, as defined in Equation (6), can vary experimentally over many decade ranges in different systems in conjunction with variation in solids specific resistance. Thus, the merits of a filter cloth used under different operating conditions or at different pressures can be compared more conveniently by means of E values obtained through performance tests.

§ Derivation is indicated in Appendix II.

5. Examples

The following examples illustrate treatment of filtration data according to the procedures outlined. Previously unpublished data were produced during development work carried out by The Fluor Corporation Ltd.

Example 1—Filtration of Reduced Copper Slurry

Particulate material in the slurry being filtered ranged in size from 0.50 to 5.00 microns. Previously conducted leaf tests indicated the filter cakes were not compressible to a measurable extent. Data for three runs, two at 10 in. Hg cake-forming pressure and one at 6 in. Hg cake-forming pressure, are given in Table I. The data for 10 in. Hg cake-forming pressure were inserted into Equation (8) to calculate specific resistance of the solids. The media resistance was calculated using the definition of σ.

The values of α and R_m were utilised to estimate the efficiency of the run at 6 in. Hg cake-forming pressure, assuming that the filter media resistance is also independent of pressure. Static head corrections for the pilot-plant filter can be neglected. The filter medium used was lightweight, unbleached, cotton muslin.

Example 2—Filtration of Calcium Carbonate Slurry with Laboratory Drum Filter

RUTH and KEMPE obtained several sets of performance data filtering a specially prepared calcium carbonate precipitate slurry with 1-ft-diameter vacuum drum filter.[11] The data obtained exhibited considerable scatter which were attributed to problems of holding constant vacuum and maintaining uniform suspension in the filter tank. One set of data, those reported for November 19, 1934, were treated statistically for removal of outlying values within 95% confidence limits. Filtration efficiency calculations obtained from the statistically treated data are presented in Table III. The original data are reproduced in Table II.

Examination of the results given in Table III can lead to further interpretation of the filtration process. It is evident that the efficiency increases as the time of submergence increases as predicted by MONDRIA'S equation. This is the result of greater cake build-up during longer cycle time which results in less proportion of pressure drop across the medium. The values of $K\alpha/R$ solved from the definition of σ indicate no trend of this ratio with the time of filtration cycle. It is therefore highly probable that the solids are not compressible.

Using the average value of $K\alpha/R$, the theoretical efficiency curve is plotted on Fig. 2 for comparison with experimental points. The plot of E versus log rpm shows the relationship between experimental points and the curve determined by average properties.

Example 3—Filtration of Microcrystalline Wax from Chilled Raffinate Stream

Reeves tabulated observed filtrate volume-time information for microcrystalline wax filtration at 0°F on a 500 ft² drum filter operating at two and four minutes per revolution.[7] For two minutes per revolution and 212 bbls. per minute filtrate flow, E is 0.875. At half the rpm and 153 bbls. per minute filtrate rate, E is 0.905 through simultaneous solution.

6. Conclusion

Under conditions of ideal filtration, e.g., no compression of filter cake and media, efficiency of filtration is described by treatment according to Mondria's equation. The efficiency of such a system is determined for any operating conditions (at the same drum differential pressure) directly

from Equation (7) for a given value of $\left(\frac{\alpha}{R_m}\right)$. The ideal condition can be readily compared to actual performance through analysis of a series of data such as treated in Example 2.

Comparison of data at different drum differential pressures, or for performance of different media in the same slurry can be also carried out with convenience. The filtration efficiency concept provides a simpler basis for analysis and comparison of data for steady-state drum filtration.

APPENDIX I—DERIVATION OF MONDRIA EQUATION

The equation for simultaneous solution for α and R_m under conditions of constant specific resistance was derived by MONDRIA using a different set of units. The derivation is repeated using the A.I.Ch.E. filtration nomenclature. Equation (6) may be written:

$$\frac{\mu}{g_c}\left[\alpha\, k\, \frac{v^2}{2} + R_m\, v\right] = p'\,\frac{\beta}{\omega} \qquad \ldots.(6)$$

This may be solved for v in the form

$$v = \frac{R_m}{k\alpha}\left(\sqrt{1 + \frac{2k\alpha p'\beta g_c}{\omega\, {R_m}^2\, \mu}} - 1\right) \qquad \ldots.(11)$$

Then by the definition

$$\sigma = \left(\sqrt{1 + \frac{2k\alpha p'\beta g_c}{\omega\, {R_m}^2\, \mu}} - 1\right) \qquad \ldots.(12)$$

For two sets of data, volume of filtrate at two different values of ω, the ratio of time rate of filtrate production is defined by

$$y = \frac{V_b}{V_a} = \frac{V_b}{V_a}\,\frac{\omega_b}{\omega_a} = \frac{x}{\sigma}\left(\sqrt{1 + \frac{2k\alpha p'\beta g_c}{\omega_b {R_m}^2 \mu}} - 1\right) \ldots.(13)$$

where σ refers to conditions at "a".

Algebraic manipulation can be used to reduce the radical in Equation (13) in the following manner:

$$\left(\frac{\omega_a}{\omega_b}\right)^{\frac{1}{2}}\left(\frac{\omega_b}{\omega_a}\right)^{\frac{1}{2}}\left[\left(1 + \frac{2k\alpha\beta p' g_c}{\omega_b {R_m}^2 \mu}\right)^{\frac{1}{2}} - 1\right] =$$

$$\frac{1}{\sqrt{x}}\left[\left(x + \frac{2k\alpha p'\beta g_c}{\omega_b {R_m}^2 \mu}\right)^{\frac{1}{2}} - 1\right] = \frac{1}{\sqrt{x}}\left[(x + \sigma^2 + 2\sigma)^{\frac{1}{2}} - 1\right]$$

since $(\sigma + 1)^2 = 1 + \frac{2k\alpha\beta g_c p'}{\omega_b {R_m}^2 \mu} = \sigma^2 + 2\sigma + 1$

Substitution into Equation (13) produces the following which reduces to MONDRIA's form:

$$y = \frac{x}{\sigma}\left[\frac{1}{\sqrt{x}}(x + \sigma^2 + 2\sigma)^{\frac{1}{2}} - 1\right]$$

APPENDIX II—DERIVATION OF EFFICIENCY EXPRESSION

In fundamental equation for rotary drum filtration, the effective pressure for filtration is expressed as:

$$p' - p_1 = Ep' \qquad \ldots.(9)$$

Integration of Equation (1) to the limit $p' - p$ results in:

$$\frac{p' - p_1}{\alpha} = q\,\frac{\mu}{g_c}\,v\left(\frac{s\rho}{1 - ms}\right) = \omega\,\frac{dv}{d\Phi}\,\frac{\mu}{g_c}\,vk$$

Further integration produces:

$$\frac{p' - p_1}{\alpha}\,\beta = \frac{\mu}{g_c}\,k\omega\,\frac{v^2}{2}$$

Substitution into $E = \frac{p' - p_1}{p'}$ results in the following, taking p' from Equation (8):

$$E = \frac{\frac{\mu}{g_c}\,k\omega\,\frac{v^2}{2}\,\frac{\alpha}{\beta}}{\frac{\mu}{g_c}\,k\omega\,\frac{v^2}{2}\,\frac{\alpha}{\beta}\left[1 + \frac{2}{\sigma}\right]} = \frac{\sigma}{\sigma + 2}$$

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The Application of Statistics to Cost Estimating

Continued from page 19

(*h*) *Standard error of* C_1*:*

$$= \sqrt{V_1}$$

(*i*) "t" *for* (n − 3) *degrees of freedom:*
obtained from Tables of the "*t*" distribution.[1, 2, 3]

(*j*) *Confidence limits for* C_1*:*

$$= C_1 \pm t \times \sqrt{V_1}$$

For more than two independent variables, such as N and A, the procedure is a little more complicated, but the computation is made easier by the use of matrix algebra to calculate the Gaussian multipliers.

Table II shows the steps (a) to (j) carried out for the data given in Table I for the particular case when $C_1 = 176$, $N_1 = 240$, $A_1 = \pi \times 1.5 \times 16 = 75.4$ and $n = 10$.

It will be seen that for this particular case the 95% confidence limits are 176 ± 62. The wide spacing is, to some extent, due to the fact that the regression equation has been derived from only ten sets of hypothetical data. In practice, it is advisable to have considerably more (e.g., 50) sets of cost values within the range to be considered.

It is thus possible to produce a regression equation which will predict labour costs with known accuracy.

After the first calculations required for deriving the equation, the time required for such a prediction is of the order of minutes compared with the hours taken by an experienced cost estimator in obtaining a labour cost estimate.

In order that the regression equations should continue to be valid, the cost data used in evaluating the regression coefficients m and p must constantly be brought up to date. A more rigorous method of analysis would be to split the total required labour *time* into the several trade components, e.g., welding, fitting, machining times, and hence produce several regression equations for the *times* required for each trade operation. Since the prevailing hourly wage rates will be known, the total labour *cost* is then easily determined. Since this multiple regression analysis simultaneously correlates more than one factor in the make-up of the cost, it is obvious that cost predictions are likely to be far more accurate than the graphical correlations, such as cost vs. tube surface area for exchangers or cost vs. volume for storage tanks.

Regression analysis has proved a very useful tool in the chemical and allied industries for the correlation of variables which are not necessarily functionally related.[4] The example given in this article indicates further the use of this statistical technique.

ACKNOWLEDGMENT

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CALCULATION OF "LEAKY" VACUUM INSTALLATIONS*

Methods of calculating the dimensions of leaky vacuum systems presented in this article include short-cut graphical procedures for estimating the permeabilities of seals, characteristics of vacuum pumps and of the pumping system in the presence of leaks. Also presented is a nomogram for determining the most economical operating conditions

by ING. A. ROTH

THE purpose of a vacuum installation is to produce a reduced pressure in a receiver. This requires the production of a reduced pressure in a given time or the maintenance of a given reduced pressure over a period of time as a function of the characteristics of the receiver.

If the receiver is "non-leaky", i.e., if after evacuation and separation of the receiver from the pump there is no change in the reduced pressure (e.g., phials, electric bulbs, radio valves), the calculation of the vacuum installation is concerned only with the production of a given reduced pressure. If, on the other hand, the receiver is "leaky" (reaction vessel, distillation flask, power rectifier, etc.), the calculations must also take into account the maintenance of the desired vacuum.

The analytical and graphical methods of calculation for non-leaky vacuum installations have been discussed in a previous paper.[1] The present contribution is devoted to special features of the calculation of "leaky" vacuum installations and to the presentation of a graphical method of calculation developed for this purpose.

1. Definition of the Leakage Coefficient

The degree of leakage of a vessel may be judged by the increase in pressure inside the vessel after it has been evacuated and separated from the pump. This development of pressure is best followed by means of a graph of pressure against time, counting zero time ($t = 0$) as the moment of separation of the receiver from the pump (for example, the closing of the stopcock separating the receiver from the pump).

The graph of the development of pressure in a receiver of volume, V, after separation from the pump, may have one of the forms (a, b, c) shown in Fig. 1. All pressure-time curves start from the point $t = 0$, $p = p_i$, where p_i is the pressure in the receiver at the moment of separation of the receiver from the pump.

The equation of these curves may be written in general form as

$$dp = \frac{f}{V}\,dt \qquad \ldots.(1)$$

In the case of curve a, Equation (1) becomes

$$p = p_i$$

i.e., $dp/dt = 0$ and hence $f = 0$. Curve a represents the case where the pressure, p_i, existing at the moment of separation remains constant, and hence represents *the characteristic curve of a "non-leaky" receiver.*

The equation for curve b is

$$p - p_i = \frac{f}{V}\,t \qquad \ldots.(2)$$

f being a constant ($f > 0$). This curve represents the case where the rise in pressure is proportional to the time. This means that the gas entering the receiver comes from a very large source and hence from outside the receiver. The general equation for curve c is

$$dp = \frac{f}{V}\,dt \qquad \ldots.(3)$$

where f has various values from $f = f_i$, corresponding to the tangent at the point $p = p_i$ to $f = 0$, corresponding to the asymptote approached by the curve. In this case the increase in pressure becomes less and less as time increases. This means that the gas derives from a finite source inside the receiver (degasing).

The value of the constant f characterises the shape of the p-t curves. For this reason, f may be *called the leakage coefficient.*

Consequently, a non-leaky receiver is theoretically defined as one having a zero leakage coefficient ($f = 0$). This implies that any receiver for which $f > 0$ is theoretically defined as "leaky".

From the general Equation (1) it follows that f has the units: pressure × volume/time and hence may be regarded as the product of the pressure and rate of infiltration or evolution of gas (being expressed as mm Hg × litres/min, mm Hg × m³/h, etc.).

If the infiltration or evolution of gas derives from different sources or in different ways, it is conceivable that each of these may be expressed by a partial coefficient $f_1, f_2 \ldots f_n$ in such a way that the total leakage coefficient, f, is given by the relation

$$f = \sum_{1}^{n} f_i \qquad \ldots.(4)$$

In the most usual case of inleakage from the outside

* Translated from *Revista de Chimie*, **11**, 78 (1960).

through gaskets, stuffing-boxes, etc., their quality is characterised by the *coefficient of permeability*, a, which is defined as the quantity of gas (generally in grams) which penetrates in unit time through unit length or area of seal. Given the proportionality between density of the gas and the pressure, we have

$$\rho_p = K \cdot p \qquad \ldots . (5)$$

where ρ_p (g/m³), p (mm Hg) and $K = \frac{\rho_{760}}{760}$. For air $K = 1.7$ g/m³ mm Hg.

Conversion is possible from the coefficient of permeability of the seal a (g/m hr) to the leakage coefficient f (mm Hg m³/h) by means of the relation

$$f_i = \frac{a_i \cdot l_i}{K} \qquad \ldots . (6)$$

where l_i is the length of the seal concerned (in m, e.g., the circumference of a gasket, a stuffing-box, etc.). The calculation is rapidly accomplished with the aid of the nomogram in Fig. 2 which includes the coefficients of permeability of the more usual types of seal.

Example: A vessel sealed with a rubber gasket (point α) from the inlet of a receiver having a diameter 32 cm, and hence $l = 1$ m (point β), has a leakage coefficient given on scale f by the point γ.

In the case of a seal whose permeability coefficient does not fit into any of the types illustrated in Fig. 2, the value of the leakage coefficient, f, may be determined experimentally. For this purpose one sets up a receiver of reduced capacity (e.g., 1 litre) and seals it off with the type of seal whose leakage coefficient, f, is to be found. The receiver is fitted with a vacuum gauge suitable for the range of pressures to be measured,[2] is evacuated with a suitable pump down to a pressure p_i, and separated from the pump. The pressure is read at various intervals of time and the p-t curve is traced (as in Fig. 1). The leakage coefficient, f_i, of the pilot-scale seal is given by the product of the slope of the curve and the volume of the pilot-scale receiver:

$$f_i = \frac{dp}{dt} V \qquad \ldots . (7)$$

while the permeability coefficient, a, of the seal investigated may be determined with the aid of the nomogram in Fig. 2 by working from f towards a.

2. Pump and Pumping Characteristics

A vacuum pump is sometimes characterised by the speed with which a given pressure may be attained, the lowest pressure (minimum) it is capable of giving, or the time taken by the pump to reduce the pressure in a vessel of definite volume by a given amount. None of these characteristics, taken individually or in their totality, is capable of completely defining the performance of a pump or of supplying the complete data necessary for establishing the operating régime of the vacuum pump under given pumping conditions. For a full appreciation of the capability of a vacuum pump, it is necessary to refer to its characteristic curve plotted in one of the systems used for the purpose.

With a view to establishing a correlation between the various systems for representing the characteristics of a vacuum pump and of the way in which one is derived from the other, the characteristic curve of a given vacuum pump is represented in its various aspects in Fig. 3 (a-d).

The system of representation most widely employed by vacuum pump manufacturers is that illustrated in Fig. 3a. Such a characteristic curve indicates the speed of pumping, S, of the pump (on the ordinate, in linear scale) as a function of the pressure, p, realised at the suction inlet of the pump (on the abscissa, in logarithmic scale). The point p_0 at which the curve intersects the abscissa ($S = 0$) indicates the limit pressure which can theoretically be achieved by the pump considered (this point is not obtained by direct measurement, but by extrapolation).

A second system of representing the characteristics of a vacuum pump is that illustrated in Fig. 3b. This curve gives the product $p.S$ (on the ordinate, in logarithmic scale) as a function of pressure p (on the abscissa, in logarithmic scale). This type of representation is rarely used by the manufacturer of vacuum pumps, but is very useful for the user, since it enables him to judge more easily the possibilities of adaptation for certain installations (the way in which this is done will be shown below).

For the determination of the duration of pumping the curve

$$\frac{1}{S} = f(\log p)$$

is plotted as in Fig. 3c. On the basis of Gaede's[4] general relation, the duration of pumping is given by:

$$t = -2.3V \int_{\log p_t}^{\log p} \frac{d(\log p)}{S} \qquad \ldots . (8)$$

This relationship in graphical form expresses the fact that the time necessary for pumping unit volume is given by the area enclosed between the curve $1/S = f(\log p)$, the axis $\log p$, and the ordinates corresponding to the pressure p, at the beginning of pumping and to the pressure, p_t, at the end of the pumping period.

By dividing the area under the curve c (*Fig.* 3) into zones corresponding to given intervals of pressure (e.g., one order of magnitude each), determining the average of $1/S$ for each interval, and calculating the product

$$\triangle \log p \, (1/S)_{av},$$

one obtains the duration of pumping for each interval. By representing these values in a cumulative manner, starting off with atmospheric pressure and working towards lower pressures (in the direction of the arrow in Fig. 3d), for every interval, at the lower pressure which demarcates the interval, one obtains the presentation of Fig. 3d. On such a curve it is possible to read off the time t necessary for the evacuation of unit volume from atmospheric pressure to the corresponding pressure, p. It must again be underlined that all these characteristic curves *refer to the pump itself*, that is, to the speed of pumping, duration and pressure measured at the suction inlet of the pump or transposed to it by calculation (if the measurements have been made in receivers attached to the pump, taking into account the conductance of the pipe connections between pump and receiver).

When using the pump the data indicated by the characteristic curves of the pump cannot be assumed to be followed also in the receiver being evacuated. If the effect of the conductance of pipe connections is not neglected until calculation has shown this to be justified, one avoids the unpleasant surprises which sometimes occur when, after constructing a plant, it is found incapable of achieving the performance for which it was designed. The error arises from the assimilation of the rate of evacuation realised in the receiver with the speed of pumping indicated from the pump characteristics.

The rate of evacuation, S_r, realised in a receiver connected by pipework of conductance C to a pump having a pumping speed S is given by:

$$\frac{1}{S_r} = \frac{1}{S} + \frac{1}{C} \qquad \ldots . (9)$$

or

$$S_r = \frac{S}{1 + \frac{S}{C}} \qquad \ldots . (9')$$

Since, independent of the values of S and C, we always have

$$1 + \frac{S}{C} > 1$$

it follows that S_r is always smaller than S, and hence the *rate of evacuation is always less than the speed of pumping of the pump.*

For pumping, Boyle's law is written

$$p \,.\, S = p_r \,.\, S_r \qquad \ldots.(10)$$

where p and S are the pressure and speed of pumping of the pump, while p_r and S_r are the pressure and rate of evacuation in the receiver.

From the above, denoting $S_r/S = N$ (Equation (11)), we have for the pressure, p_r, in the receiver the expression:

$$p_r = p \,.\, \frac{S}{S_r} = p/N \qquad \ldots.(12)$$

Because $S_r < S$ $(N < 1)$ we always have $p_r > p$, and hence the *pressure in the receiver is always greater than that at the pump.*

The transfer from the pump characteristics to the conditions of evacuation in the receiver is accomplished with the aid of Equations (9) to (12). It can be effected by starting off with the curve, $S = f$ (log p) (Fig. 3a) and calculating point for point the corresponding values of S_r and p_r. In this way one obtains the curve $S_r = f$ (log p_r) (Fig. 3e).

In the construction of the curve (Fig. 3f) equivalent to that of Fig. 3b—although the relation (10) enables direct transformation from $p \,.\, S$ to $p_r \,.\, S_r$—it is nevertheless necessary to calculate the individual values of S in order then to be able to find the values of p_r (Equation (12)). As in the case of the transformation from curve 3a to 3e, the transformation to 3f can only be made point for point.

From the curve $1/S = f$ (log p) (Fig. 3c), it is possible to construct graphically the curve $1/S_r = f$ (log p) by adding to the ordinate of every point of the curve the value $1/C$ (Equation (9)). The curve which results is that denoted by $1/S_{rp}$ in Fig. 3g. The value of N can be plotted on the same figure; each point N results from the ratio of the ordinates of the curves $1/S$ and $1/S_{rp}$, since according to Equation (12):

$$N = \frac{S_r}{S} = \frac{1}{S} \div \frac{1}{S_r} \qquad \ldots.(12')$$

With the aid of curve $1/S_{rp}$ and N, it is then possible to construct the curve $S_r = f$ (log p_r) of Fig. 3e, the ordinates of the points being the inverse of the values indicated by the ordinates of the curve $1/S_{rp}$ (Fig. 3g), while the abscissae are given by the ratio of p and N.

From the curve $S_r = f$ (log p) (Fig. 3e), it is then possible to construct the curve of Fig. 3f directly.

The difference between pump and evacuation characteristics is best illustrated by a comparison of the curves of Figs. 3a and 3e. This pair of curves does not, however, allow reading off the values of S_r and p_r at the receiver corresponding to given values of S and p of the pump.

The system of representation of Fig. 3b and 3f does not reveal the deformation of the pump curve transposed at the receiver, but enables direct reading-off of the value of p_r existing in the receiver at the moment when the pressure in the pump is p (e.g., to the pressure p—point γ there corresponds p_r—point $\varkappa$).

The direct reading of a pair of S_r, p_r corresponding to a pair S, p can only be made with the aid of a diagram composed of four curves of the type of those of Fig. 3a, b, e, f. Starting off from S (point α) on such a diagram, one passes to point β and finds the pressure p (point γ). Passing then on the vertical to the curve of Fig. 3b, one finds the point δ. The point on the horizontal of Fig. 3f corresponding to point δ is point ϵ. The vertical of the point indicates the pressure in the receiver, p_r (point χ); the intersection of the vertical with the curve of Fig. 3e (point λ) determines the rate of evacuation in the receiver (point μ).

Besides the curves shown in Fig. 3, it is also usual, in the case of vacuum pumps, to plot curves of the type illustrated

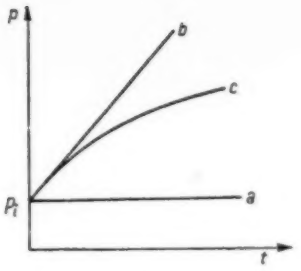

Fig. 1. Development of pressure in an evacuated receiver.

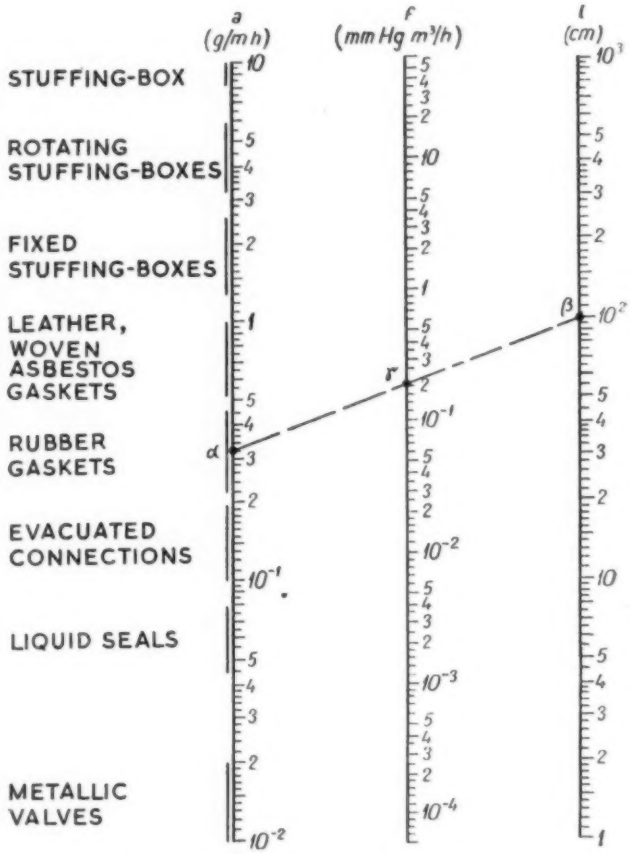

Fig. 2. Calculation of the leakage coefficient.

in Fig. 4. These curves indicate the power consumed by the pumps as a function of the pressure, p, realised at the suction inlet of the pump. From the curve it is seen that, starting off at atmospheric pressure, the power consumed by rotary oil vacuum pumps rises at first and then falls to a minimum, after which it rises again.

The bearing that this shape of the curves has on the choice of the pumping régime will be shown in Section 4.

3. The Characteristics of the Pumping Régime for "Leaky" Receivers

In the course of evacuation of a non-leaky receiver the pressure in the receiver falls continuously and tends towards the limit pressure, p_0, of the pump. This is not so in the case of leaky receivers; in this case the pressure in the

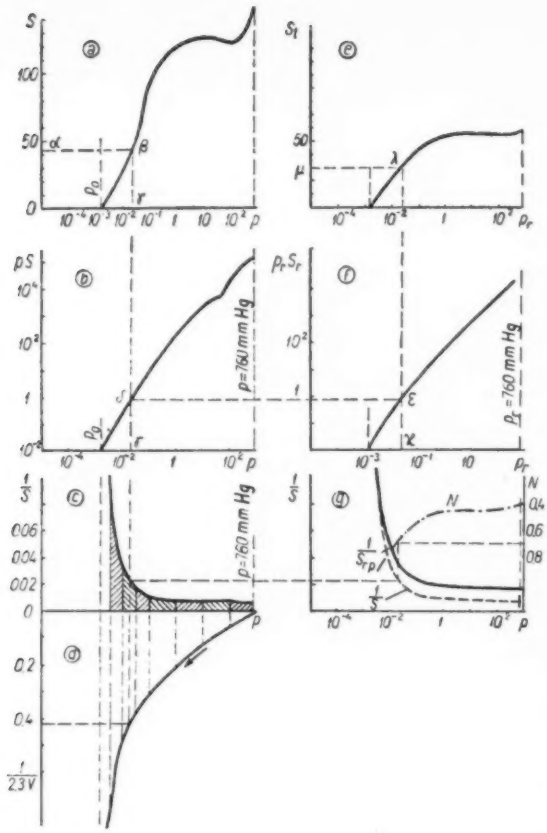

Fig. 3. Various systems of representing pump and pumping characteristics.

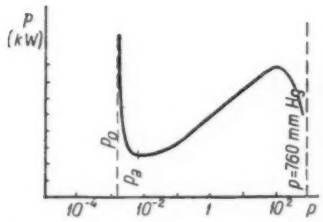

Fig. 4. Curve of P (*power consumed*) *as a function of* p (*pressure at the suction inlet of rotary vacuum pumps*).

receiver cannot fall below a given critical pressure, p'. The product $p_r \,.\, S_r$ (Fig. 3f) falls as evacuation proceeds, independent of the type of receiver. For a receiver having a leakage coefficient f, the product $p_r \,.\, S_r$ continues to fall as long as it is larger than f. The moment the equality

$$p_r \,.\, S_r = f \qquad \ldots . (13)$$

is reached, *the pressure in the receiver stabilises itself*. The critical pressure is therefore the pressure p', given by the equation

$$p' = f/S_r \qquad \ldots . (14)$$

From Equations (9) and (10) we obtain:

$$p_r = p \,.\, \frac{S}{S_r} = p \,.\, S\left(\frac{1}{S} + \frac{1}{C}\right) = p\left(1 + \frac{S}{C}\right) \qquad \ldots . (15)$$

For the same relation L. DUNOYER[5] gives the formula

$$p_r = p \,.\, \frac{1}{1 + \frac{S}{C}}$$

Transforming this formula (on the basis of the general Equation (9)), one arrives at

$$p_r = p \,.\, \frac{S_r}{S}$$

which would mean that the pressure, p_r, is always smaller than p, which is impossible. Clearly, all the other conclusions drawn by L. DUNOYER on the basis of this formula must be wrong too. For instance, the conclusion that the fall of p' is partly due to a fall of the pressure p at the suction inlet of the pump, and partly due to a fall in the factor $\frac{1}{1 + S/C}$ as the value of S increases, is qualitatively also in error. Quantitatively, it is possible for an increase in the speed of pumping, S, to be accompanied by a decrease in the value of p', on condition that the decrease of the factor p should be greater than the increase in the value of the factor $(1 + S/C)$ of Equation (15). The minimum conductance of the pipe connections which is necessary for a pump having a pumping speed S to evacuate the enclosed space of a receiver at the rate S_r is given—according to L. DUNOYER[5]—by

$$C_{min.} = \frac{S_r}{1 - S/S_r}$$

But, starting off from Equation (9), there results

$$\frac{1}{C} = \frac{1}{S_r} - \frac{1}{S}$$

or

$$C_{min.} = \frac{S_r}{1 - S_r/S} \qquad \ldots . (16)$$

On the basis of Equations (16) and (14), there results

$$C = \frac{f}{p' \,.\, (1 - N)} \qquad \ldots . (17)$$

On the basis of Equations (15) and (17) the nomogram of Fig. 5 has been constructed. This nomogram enables the following:

determination of the pressure p' and of the factor N, if S, C and f are known;
determination of S and N, if C, f and p' are known;
determination of p' and f, if S, N and C are known;
determination of C and S, if f, N and p' are known.

The method of using the nomogram is indicated by the example actually traced in Fig. 5; starting off on scale S (point α) and scale C (point β), one determines point γ (scale S_r). The intersection of the vertical through point γ with the corresponding f curve (point δ) determines the pressure p' (point ϵ). If S, S_r and C are read off from the scales whose figures are given in brackets, the values of f must also be chosen from those given in brackets. The intersection of the straight line ϵ-η determines the point λ, while the intersection of the straight line λ-μ determines the point ν (value of N).

In order to extend the range of applicability of the nomogram in Fig. 5 as far as possible, the scales S, S_r and C have not been expressed in any particular units so as to be valid for any units in which they can be expressed: cm³/s, litre/min, m³/h, l/s—as long as the same units are used throughout for these quantities. Similarly, f must be expressed in the units appropriate to those of the product formed with the units selected for S, such as mm Hg. cm³/s,

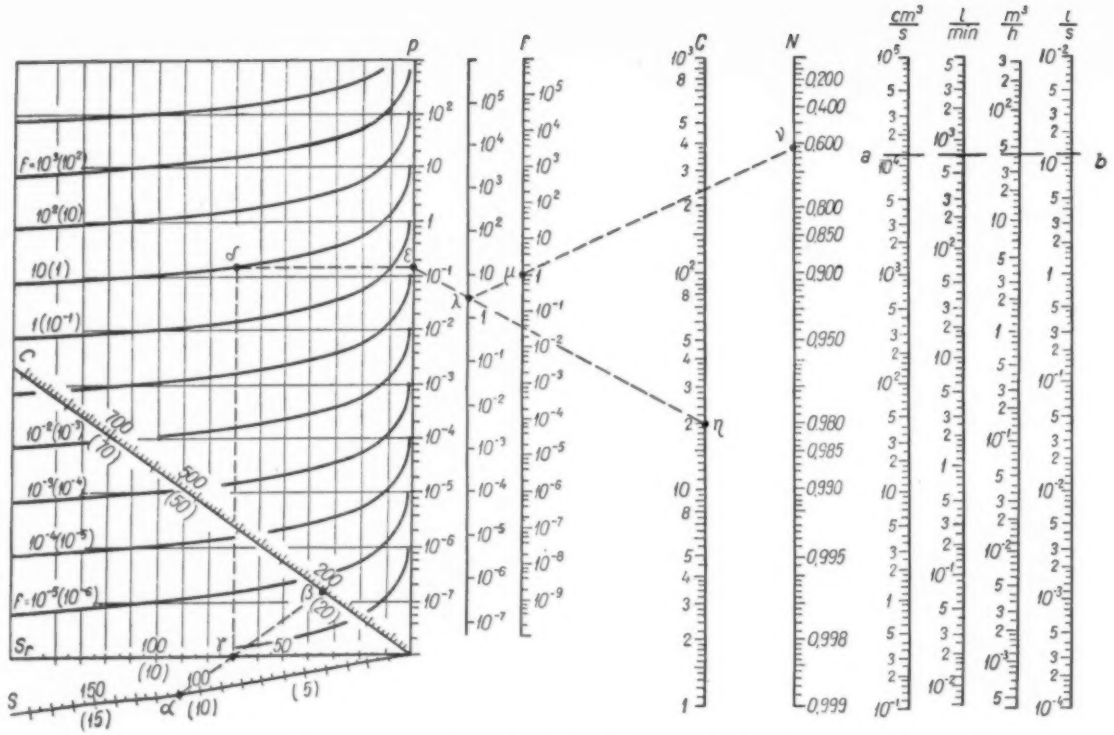

Fig. 5. Combined nomogram for the determination of the pumping characteristics of "leaky" receivers.

mm Hg. litre/min, etc. In order to facilitate the conversion from one scale to another, parallel scales constructed for the purpose are included on the right-hand side of the nomogram (Fig. 5). Readings on the two scales of interest are taken at the intersections with the horizontal line (e.g.: *a-b*).

4. Economic Criteria for the Selection of the Pumping Régime

From the curves $P = f(p)$ (Fig. 4) of the pump it is seen[6] that for rotary oil pumps the power consumed is a minimum at a pressure, p_s given in general by

$$p_s \simeq 2\,p_0$$

where p_0 is the limit pressure of the pump. It is normal for the pump to operate the more economically the nearer the pressure of the régime approaches the value p_s. In the ideal case

$$p_{ec} = p_s = 2\,p_0 \qquad \ldots.(18)$$

Due to the fact that the slope of the curves is lesser from p_s towards higher pressures than between p_s and p_0, if the pressure of the régime cannot be made equal to p_s, it is more economical if it is a little higher. Thus, one may indicate a region of pressures for economic operation given by:

$$2 < \frac{p_a}{p_0} < 4$$

For calculations one may therefore take $p_s = 3\,p_0$, which value, when related to Equation (14), determines S_{ec}:

$$S_{ec} = \frac{f}{3\,p_0} \qquad \ldots.(19)$$

When designing for operation under economic conditions with a pump of given p_0 and a receiver of given f, one starts in Fig. 5 with the value S_{ec} given by Equation (19).

Conclusions

For the calculation of a "leaky" vacuum installation it is necessary to know the leakage coefficient, f. This may be ascertained with the aid of the nomogram in Fig. 2, either by making use of the values of the permeability coefficient of a given range included in the diagram, or by determining the coefficient of permeability experimentally, on a pilot scale (in the manner described in Section 1).

The evacuation curve of the receiver shows the stabilisation of the pressure in the receiver at a critical value p' (Equation (14)) determined by the leakage coefficient and the rate of evacuation from the receiver.

Taking into account the correlation between the curve of the pump and the evacuation curve (Fig. 3), the operating pressure which one attains in the receiver is a function of the leakage coefficient, the conductance of the pipe connections, and the ratio N (Equation (17)). The nomogram of Fig. 5 permits the determination of some of these characteristics as a function of the known characteristics.

The characteristics for the most economical operation may be determined with the aid of the same nomogram making use of the value S_{ec} determined from Equation (19).

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RECENT ADVANCES IN HEAT TRANSFER

The most recent joint heat transfer conference of the A.I.Ch.E. and A.S.M.E.* brought forth many papers of interest to chemical engineers. Most of them are summarised in this article. Subjects dealt with are heat transfer in the critical region, laminar film condensation upon flat plates and horizontal tubes, radiation and a method of investigating heat transfer ratios in evaporators

THE aspects of heat transfer covered by this Conference were, broadly speaking, those of radiation, convection, heat transfer associated with changes of phase and in the presence of particulate solids. A number of recent techniques such as those of wick-boiling and film cooling were treated, and a few new design procedures made their début, notably one for estimating the surface area of dehumidification equipment and another for the drying of solids in a fluidised bed.

Before passing to an outline of papers dealing with heat transfer accompanied by change of phase, mention will be made of a paper given by HSU and SMITH (paper 60 HT8).

Heat Transfer in the Critical Region

In opening this paper, its authors note that conventional ways of dealing with changes in fluid properties in heat-transfer coefficient equations do not apply when the fluids are near the critical point.

For example, when the density changes transverse to the flow of a fluid in heat transfer within a tube, the variable density can affect the transfer of momentum and heat. In the case of vertical tubes variation in the force of gravity across the tube diameter can induce natural convection. A quantitative treatment of each of these effects was the purpose of these two authors in their paper. In their treatment of the subject they consider first the effect of density variations upon the transfer of heat and momentum and they represent the variation of density by the following equation:

$$\frac{\rho}{\rho_o} = a\left(\frac{T}{T_o}\right)^{\alpha}$$

Temperature and velocity profiles across tube are obtained by integrating the equations for momentum and energy transfer, a method proposed by Deissler being used for this purpose.

From the profiles, equations are obtained by integrating the equations for momentum and energy transfer, a method proposed by Deissler being used for this purpose.

$$t_b{+} = \frac{\int_0^{r^+} \left(\frac{C_p\rho}{C_{po}\rho_o}\right) t{+}U{+}(r{+} - y{+})dy{+}}{\int_0^{r^+} \left(\frac{C_p\rho}{C_{po}\rho_o}\right) U{+}(r{+} - y{+})dy{+}}$$

and the Nusselt number (properties evaluated at wall temperature) is given by:

$$\mathrm{Nu}_o = \frac{2rh}{k_o} = \frac{2r{+}\mathrm{Pr}_o}{t_b{+}}$$

To elucidate the effect of natural convection for turbulent flow in tubes they examine the effect of body force on the distribution of sheer stress in the fluid. To show the effect of natural convection a plot of Reynolds vs. Nusselt number is made with Grashof numbers as parameters (Fig. 1).

The effect of natural convection is to flatten the velocity profile and to increase the heat-transfer coefficient. The equations were applied to experimental results reported in the literature for the flow of CO_2 in the critical region. For the conditions of these results typified by high Reynolds and low Grashof numbers, the contribution of natural convection to the heat transfer is unimportant. But the density variation is significant and the predicted results agree well with the data for CO_2.

Symbols Used

C_p = specific heat at constant pressure;
q = heat flux, Btu/hr sq ft;
r = tube radius, ft;
r^+ = dimensionless radius
$= r\left(\frac{\tau}{\rho_o}\right)^{\frac{1}{2}}\left(\frac{\rho_o}{\mu_o}\right)$;
T = temperature, °R;
t = temperature, °F;
t^+ = dimensionless temperature
$= \frac{1}{\beta}\left(1 - \frac{T}{T_o}\right)$;
U^+ = dimensionless velocity
$= U\left(\frac{\tau_o}{\rho_o}\right)^{-\frac{1}{2}}$
y = distance from the tube wall, ft;
y^+ = dimensionless distance
$= y\left(\frac{\tau_o}{\rho_o}\right)^{\frac{1}{2}}\left(\frac{\rho_o}{\mu_o}\right)$;
$\beta = \frac{q_o(\tau_o/\rho_o)^{\frac{1}{2}}}{C_{po}\tau_o T_o}$, dimensionless;
ρ = density, lb/ft³;
τ = shear stress, lb ft/(hr² sq ft).

Subscripts
b = denotes bulk mean value;
o = denotes value of quanitity at the tube wall.

Superscript
$^+$ = denotes dimensionless form.

Heat Transfer Accompanied by Phase Change

In many processes, such as the evaporation of heat-sensitive materials in tubular evaporators, equipped with heated surfaces of low thermal conductivity, the decisive operating variable is the heat-transfer resistance through a thin layer of thermal decomposition products deposited upon the tube interior. In the study of heat transfer in the presence of fouling, there is need for a method of measuring the fouling resistance directly, a requirement which led to the method presented by MORGAN and CARLSON (paper 60-HT-1).

This consisted of converting the tube of their single-tube evaporator into a series of resistance thermometers. They found this device capable of evaluating the mean wall temperature over a short interval to ±4°F for a single observation upon a

* First National Heat Transfer Conference and Exhibit sponsored jointly by the Heat Transfer Divisions of the A.I.Ch.E. and the A.S.M.E., August 1960.

stainless-steel tube. The heat flux conditions to which this degree of accuracy applies are less than 1,200,000 Btu/hr sq ft in the case of a stainless-steel tube. In the case of a copper tube, this accuracy applies to heat fluxes less than 3,900,000 Btu/hr sq ft. The method, extended to measure heat flux passing through a tube wall, is accurate to about ±20,000 Btu/hr sq ft. The two methods may be combined to provide a means of calculating wall surface temperatures of single-tube experimental evaporators.

Laminar Film Condensation on Flat Plates

In an analytical study of laminar film condensation, MING CHEN solves the boundary layer equations of momentum and energy for the case of laminar film condensation at a flat vertical plate. This analysis employs the more realistic boundary condition of stationary vapour remote from the interface instead of that of zero velocity gradient at the interface, as assumed by previous investigators who thus neglected the drag due to initially stationary vapour, an effect comparable to the acceleration within the condensate film.

To solve the condensation problem momentum and energy equations are set up in the integral form, using the boundary layer assumptions. For the solution of velocity profiles an internal momentum balance is made, whereas for temperature profiles an internal energy balance is used. The equations are soluble by perturbation methods.

One of the results of this analysis is an expression for the ratio of the actual Nusselt number to that obtained from the simple Nusselt theory, as given by:

$$Nu_{l,oo} = 0.943 \left(\frac{g\rho(\rho-\rho_v)l^3\lambda}{\mu k \Delta t} \right)^{\frac{1}{4}},$$

$$\frac{Nu_l}{Nu_{l,oo}} = \left(\frac{B}{B_{oo}}\right)^{\frac{1}{4}} \left(\frac{A_{oo}}{A}\right)^{\frac{1}{4}} \left(\frac{1 + D\zeta}{1 + \frac{5}{3}\frac{CB}{A}\frac{\xi}{1+D\zeta}} \right)^{\frac{1}{4}}$$

In this equation values of A, B, C and D are obtained from previous solutions of velocity and temperature profiles.

Values of this ratio are plotted against the heat capacity parameter and the momentum parameter for different values of the Prandtl number are shown in Figs. 5 and 6 of this paper. Another quantity of interest to designers is the condensation rate and the following expression for a dimensionless condensation rate is derived.

$$\frac{\Gamma}{\Gamma_{oo}} = \left(\frac{B}{B_{oo}(1+D\zeta)}\right)^{\frac{1}{4}} \left(\frac{A}{A + \frac{5}{3}\frac{CB\xi}{1+D\zeta}} \right)^{\frac{1}{4}}$$

This relation is plotted in Fig. 2.

The previous theoretical results can be approximated within 1% by the following relation:

$$\frac{h_m}{h_{m,oo}} = \left(\frac{1 + 0.68\zeta + 0.02\zeta\xi}{1 + 0.85\xi - 0.15\zeta\xi} \right)^{\frac{1}{4}}$$

$$\frac{\Gamma}{\Gamma_{oo}} = \frac{h_m}{h_{m,oo}} \frac{1}{1 + 0.345\zeta + 0.020\zeta\xi^2 - 0.0005\zeta\xi^3)}$$

The range of application of these equations are, heat capacity parameter up to 2, and the momentum parameter up to 20; and for liquids with Prandtl numbers greater than 1, or less than 0.05.

Laminar Film Condensation on Horizontal Tubes

This work was extended to single and multiple horizontal tubes. For the single tube, the inertia effects are included and the vapour is assumed to be stationary outside the vapour boundary layer, and it is also assumed that the product of vapour, viscosity and density is very much less than the same product for the liquid phase.

It is well known in practice, that in the case of multiple tube arrangements, the lower tubes give very much higher heat-transfer rates than Nusselt's theory predicts. One explanation attributes this to splashing and to random spilling-effects difficult to predict. While MING CHEN believes these effects to be important, he also considers that condensation and momentum gain in between tubes may also contribute to increased rates of heat transfer.

These effects are also considered for vertical tube banks. The momentum effect, which cannot be treated by the boundary layer theory, is expected to be of the same order of magnitude as the momentum parameter so that it cannot be neglected in an analysis where other momentum effects are included. For this

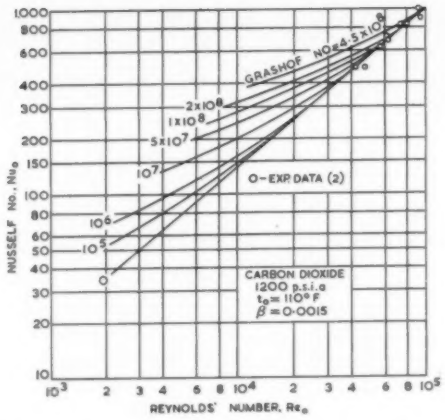


Fig. 1. Nusselt number versus Reynolds number, with Grashof number as parameter.

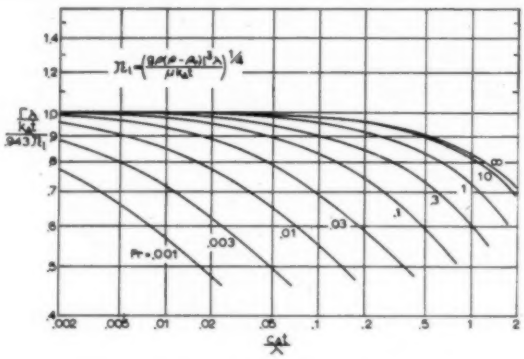


Fig. 2. Theoretical condensation rates.

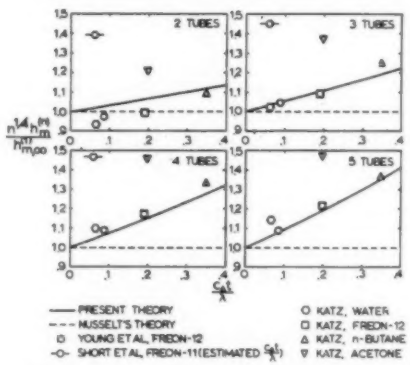


Fig. 3. Comparison of multiple-tube theory with experimental data.

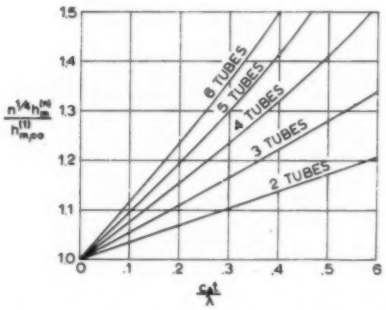


Fig. 4. Average heat-transfer coefficient for a vertical bank of n horizontal tubes.

reason, the interest is restricted to the case where the acceleration-effect parameter = 0. This is not a serious restriction, since, for most fluids, Pr > 3 and the acceleration-effect parameter < 0.1. The following equation represents the departure of the condensation heat transfer for vertical banks of horizontal tubes from Nusselt's theory.

$$\frac{h_m^{(n)}}{h_{m,oo^{(1)}}}\, n^{\frac{1}{4}} = n^{-\frac{1}{4}}\left[\sum_{i=0}^{i=n-1}(1 + D\zeta)^{4n/3}\right]\left(\frac{B}{B_{oo}}\right)^{\frac{1}{4}}(1 + D\zeta)^{\frac{1}{4}}$$

The theory produced by MING CHEN predicts a higher rate of heat transfer through condensation occurring in between tubes; theory and condensation results reported in the literature are compared in Fig. 3. The lower limits of the data follow the trend of the theoretical curve closely, thereby supporting the view that condensation takes place in between tubes. The fact that some of the data lie above the theoretical line can be explained on the basis of splashing and dripping which did not take place in those of the tests which agreed with theory. For the design of condensing equipment it is considered that no allowance should be made for these phenomena, since they are unpredictable. For this reason Fig. 4 is suggested for use in preference to empirical equations which do not take account of variation in the heat capacity parameter.

The results obtained can be represented to within 1% of the theoretical value, by the following equation

$$\frac{h_m^{(n)}}{h_{m,oo^{(1)}}}\, n^{\frac{1}{4}} = [1 + 0.2\zeta(n-1)]\left(\frac{1 + 0.68\zeta + 0.02\zeta\xi}{1 + 0.95\xi - 0.15\zeta\xi}\right)^{\frac{1}{4}}$$

which applicable to the following conditions: Pr ≤ 0.05, or Pr ≤ 1; heat capacity parameter (ξ) ≤ 2; momentum parameter $\xi \leq 20$ for single tubes, or ≤ 0.1 for multiple tubes and $\zeta(n-1) \leq 2$. For multiple-tube calculations the momentum parameter ξ may be neglected if it is less than 0.3.

Symbols Used

$A = \left.\frac{\partial u^+}{\partial y^+}\right]_{y^+=0}$ (dimensionless);

$B = \left.\frac{\partial t^+}{\partial y^+}\right]_{y^+=0}$ (dimensionless);

$C = \int_0^1 u^+ 2\, dy^+$ (dimensionless);

c = specific heat of constant pressure;

$D = 1 - \int_0^1 u^+ t^+ dy^+$ (dimensionless);

g = gravitational constant;

h = heat-transfer coefficient;

h_m^n = mean heat-transfer coefficient for n-horizontal tubes in a vertical row;

k = thermal conductivity;

l = total length of flat plate;

$\mathrm{Nu}_l = h_m l/k$ (dimensionless);

$\mathrm{Pr} = c\,\mu/k$ (dimensionless);

q = heat-transfer rate;

t = temperature;

$t^+ = (t - t_w)/\triangle t = (t - t_w)/(t_i - t_w)$ (dimensionless);

$\triangle t = t_i - t_w$ (dimensionless);

u = velocity of liquid in x direction;

$u_a = \frac{1}{y_i}\int_0^{y_i} u\, dy$

u_v = velocity of vapour in x direction;

$u^+ = u/u_a$ (dimensionless);

y = co-ordinate measuring distance normal to plate;

$y^+ = y/y_i$ (dimensionless);

μ = viscosity;

ρ = density;

ρ_v = density of vapour;

λ = latent heat of vaporisation;

$\zeta = c\triangle t/\lambda$, heat capacity parameter (dimensionless);

$\xi = k\triangle t/\mu\lambda$, acceleration effect parameter (dimensionless).

Subscripts

oo = pertaining to the case $\zeta = \xi = 0$, i.e., neglecting heat capacity and acceleration effects;

i = pertaining to liquid side of liquid-vapour interface;

m = pertaining to the overall mean value;

v = pertaining to vapour.

Superscript

$+$ = pertaining to dimensionless velocity and temperature profiles; see u^+, t^+, y^+.

Radiation Heat Transfer

Among papers coming within this sphere was one discussing the performance of Dowtherm vaporisers equipped with fast reaction-type burners (paper 25). Its authors, J. H. BORN and M. L. JONES (Foster Wheeler Corporation, New York), observed an improvement in the performance of the furnace, reflected in a lower furnace temperature and high heat adsorption rate, which they attributed to the rotary motion of the flame mass and to its greater luminosity.

MACKAY and LEVENTHAL (North American Aviation Inc.) were interested in the radiant heat transfer from a flat plate uniformly heated on one edge and from a tapered thin surface with constant temperature gradient uniformly heated at the root (papers 23/24). They propose a method of calculating the amount of heat that can be rejected from tapered thin surfaces by radiant interchange with these surroundings and, in addition, they provide graphs to help the designer choose the optimum plate dimensions for heat rejection by radiation.

In greater detail the remaining papers in this field are summarised below.

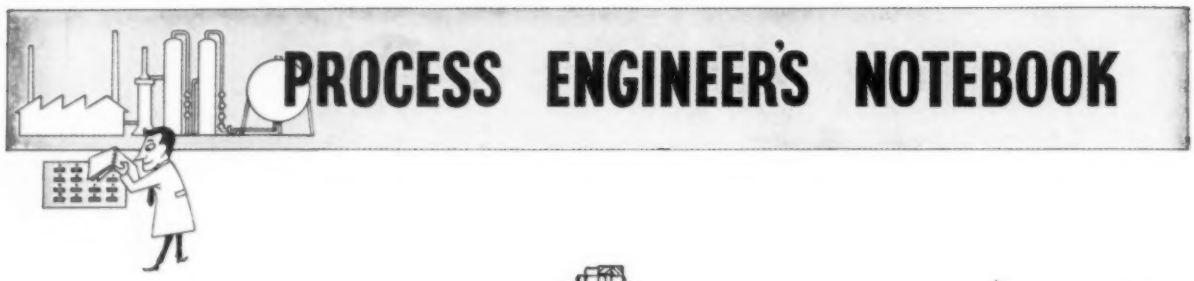
Radiant Heat-transfer Analysis of a Furnace or Other Combustion Enclosure

Closely related to practical problems was an analysis of heat transfer by radiation within a furnace or other combustion space. The method usually applied to heat transfer in furnaces, developed some years ago by LOBO and EVANS, is based upon an idealised furnace geometry and combines theory with experimental results to obtain an empirical solution for the radiation heat transfer. The method proposed by BEVANS (60-HT-12) considers the actual furnace geometry, the radiation properties of a surface are not restricted to a single value and the heat flow and/or temperature is an average value for a particular surface and not the entire heat transfer area of the furnace. BEVANS' proposed method, like the earlier LOBO and EVANS' procedure, assumes the gas to be isothermal and does not distinguish between oil and gas flows.

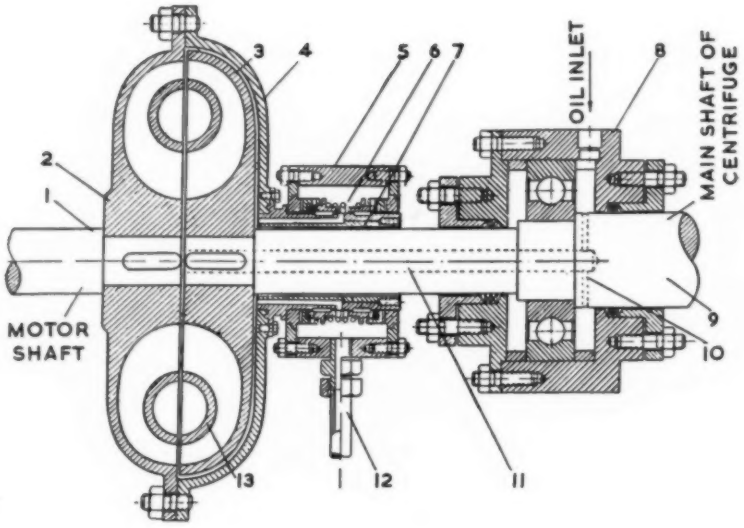
In developing his method, BEVANS introduces a quantity which forms the starting point of his procedure. This is the radiosity, defined as the sum of emitted and reflected incident radiation from a surface and whose total for a given surface is a linear combination of the total emissive power of the surface and the heat flow. A series of equations are given including two which give the total radiosity when either the effective radiation temperature of the gas or the heat flow is given. The temperature, which is not necessarily a physically measurable quantity, is determined by a heat balance on the gas.

The series of equations for radiosities, emissive powers and heat flows which are conveniently tabulated in the paper, involve the splitting up of the enclosing surface into its geometrical parts. If, for example, the black body emissivities and heat flows for some of the surfaces are known then the number of simultaneous algebraic equations requiring solution will be less than the number of surfaces. In the case of a surface which does not "see" itself the number of equations and the number of surfaces are identical. For solution of the radiosity equations various methods are available, i.e., matrix, relaxation and repetitive substitution. After radiosities have been computed, the heat flows may be calculated for the separate surfaces by means of one of the equations derived.

However, its author points out that this interesting method cannot be widely used at present because of the shortage of certain essential data; for example, geometric transmissivities, emissivities and absorptivities for various configurations. The sole data on tube banks for example are those of HOTTEL for infinitely long tubes adjacent to an infinite wall; also, emissivity values for furnace surfaces is scanty.



Variable Speed Drive for Centrifuge



AT A PLANT producing crystalline products (e.g., ammonium sulphate) which are separated from their mother liquors by means of centrifuges with 800-mm-diam. baskets, operating at speeds in the range 560-650 rpm, tests showed that the centrifuging operation was best carried out at variable speeds within the range 600-1200 rpm.

Efforts were therefore directed to making a simple means of controlling the rotary speed of the centrifuges, one which could lend itself to remote control. Accordingly, a hydraulic coupling was chosen to replace the original V-belt transmission, and its filling of hydraulic fluid was made variable in order to provide adjustment to the speed. This was done by allowing some of the liquid to overflow from the hydraulic circuit.

The following are the main features of this drive and its method of operation.

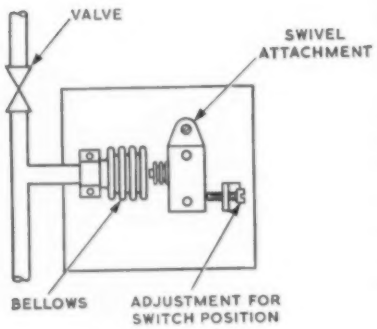
The oil is fed under slight pressure to the main bearing of the centrifuge shaft at point (8) in the illustration. From here it passes through four radial holes (10) into a central channel (11) into the hydraulic coupling. Four ducts in the rotating part of the coupling (4) allow the oil into the fixed body of coupling (5), which is fitted with the mechanical seal (6). The oil is discharged from this component through the branch pipe (12). It is the rate of this discharge which governs the speed of the centrifuge mainshaft. The oil circulates in the system at a rate of 0.5 litres/sec.; the mainshaft (9) of the centrifuge and the rotating cup (4) are sealed by means of fitting (7). An advantage of circulation is that it allows the oil to be cooled should it become overheated during the operation of the coupling.

For the particular coupling used for this modification, approximately 11 litres of liquid are required in the circulating system, in order to transmit the maximum moment to the turbine wheel (3) and at the maximum speed of the centrifuge shaft.

From *Coke and Chemistry* (USSR), No. 6, 1960.

Simple Low Flow Alarm

THE DIAGRAM SHOWS a simple method of providing an alarm for the cooling water supply to high-temperature pump-bearings, small condensers, diffusion pump or other equipment requiring a supply of cooling water. The pipeline conveying the water contains a side branch to which is fitted a bellows closed at its remote end. This is in contact with the plunger of a microswitch, the position of which can be adjusted by means of a set screw, the switch itself being arranged to swivel around its single screw mounting. The sensitivity of this device depends upon the stiffness of the switch and bellows and the resistance of the water-line outlet. This latter can be controlled by means of a small needle or pinch valve fitted downstream of the side arm. If tubing of $\frac{1}{4}$ in. bore is used, the switch can be made to operate at flow rates between $\frac{1}{4}$ and 2 litres per minute with a sensitivity of make and break of 0.1 litres per minute. Since microswitches are fitted with three contacts, it is possible to arrange for the expansion of the bellows to open the circuit, which is the situation under normal operation. If the flow of liquid falls to a dangerously low level or stops altogether, the contraction of the bellows closes the switch and actuates an alarm.



(Based on an article in *Journal of Sci. Inst.*, 1959, **36**, 98.)

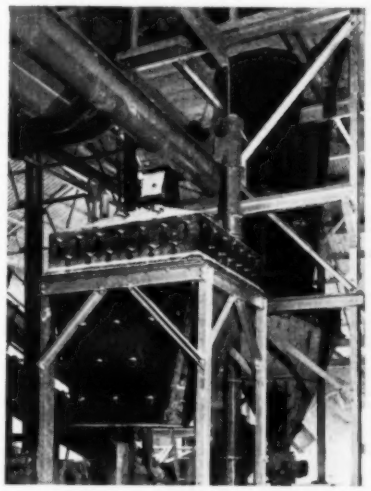
Plastic Lining Reduces Costs at Drying Plant

THE USE OF PVC paste lining for equipment used in a china clay pulverising and drying unit resulted in a useful reduction in cost. In the process dehydrated particles of clay are forced by a blast of hot air into a chimney where they are collected before being released into a hopper for packing. (See accompanying illustration.) It was necessary for the chimney to withstand not only the corrosive action of sulphur trioxide present, but also the erosion of the chimney by particles of clay. The latter is especially undesirable, because its occurrence would cause the contamination of the clay with metal particles.

It was thought at one time that a natural rubber lining would be the answer to this problem, but its use revealed rubber to be unsuitable through its poor ageing properties. A much more satisfactory solution was found to be the application of a PVC paste to the chimney interior surface. This was found to offer a surface with satisfactory corrosion and abrasion resistance, coupled with good adherence to the base metal. Compared with rubber lining, the PVC coating has cut the first cost of lining by 10% and at the same time has provided a much more durable form of protection.

In addition, a further saving has been achieved by lining the chimney externally. Previously, lagging had been provided to ensure that the temperature within the chimney did not reach the dewpoint before the clay could be discharged. The operating conditions, however, were such that the magnesia lagging had a comparatively short life of about two years. The external cover offered by the PVC paste has given sufficient insulation to prevent condensation and has proved much more durable.

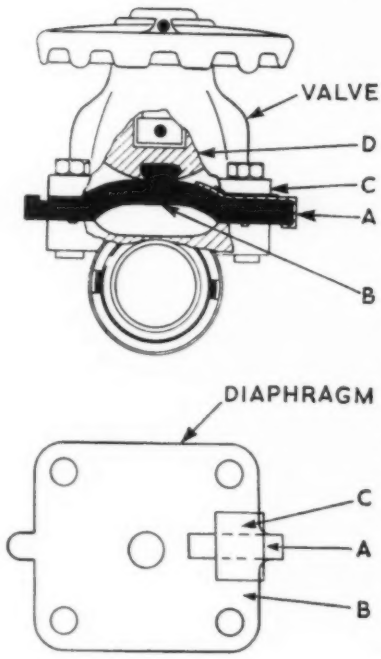
(Published by courtesy of British Geon Ltd.)



Avoiding Corrosion

ONE QUESTION WHICH the engineer should always ask himself in designing equipment for corrosive conditions is whether it is necessary for it to last for ever in its corrosive environment. If it is found that the replacement of part of a unit is feasible, then the particular component must be designed for easy replacement. Specification of surface finish is also sometimes necessary. If the interior of a piece of equipment can only be cleaned by flushing, then its surface should be more highly polished than one which, being exposed, is easily cleaned, given the same corrosive fluid. Another good point, when a concentrated corrosive fluid is being introduced into a metal vessel, in which it will be present at a lesser concentration, is to direct it to the centre.

Vacuum Valve Indicator Light



IT IS OFTEN NECESSARY to have a signal to show whether a valve is open or closed. This is simple enough with some types of valve, such as when the handle makes less than a revolution, such as is the case with a plug cock; with diaphragm valves, however, it is much more difficult to tell from the handwheel whether such a valve is open or closed, and to overcome this difficulty the modification illustrated was devised.

The diaphragm valve shown, a component of a vacuum system, has a piece of aluminium foil (A) cemented to its diaphragm: the foil is insulated from the body of the valve by tape C. When the diaphragm driver (D) depresses the diaphragm against the seat, it makes electrical contact with the foil. Thus, by connecting to a warning light and a low voltage supply, a simple alarm system is provided.

Abstracted from *Journal of Scientific Instruments*, 1959, 36, 141.

Contributions invited

THE EDITOR invites readers to submit, for possible publication in "Process Engineer's Notebook", notes on practical devices that have been elaborated on the job for improving the operation or increasing the safety of processes, or that have been extemporised in special circumstances. The contributions preferably should be of about 250-500 words, and be illustrated with a line diagram or sketch, or a photograph. A minimum of three guineas will be paid for each contribution used. They will be published anonymously or under the contributor's name, according to his wishes.

AMERICAN LETTER

The 1960 I.S.A. Show

THE fifteenth annual Conference and Exhibit of the Instrument Society of America was held last September in New York. Supplementing the numerous lectures and seminars and every aspect of instrumentation was a large exhibition held in the Coliseum, in which nearly 400 firms took part. In addition to the many complex communications and military electronic devices displayed, there was a good proportion of instrumentation and control equipment for industrial process use. Typical items of interest and of recent origin are described below.

Valves

One unusual item shown was the Bendix fluidal valve, which incorporates all the actuating mechanism within the valve body and employs only one moving part. This is an internal sleeve which is actuated by air pressure and slides in a direction parallel to the fluid flow, to give the designed flow rate. Closure is effected by the down-stream lip of the sleeve seating on an internal plug which is centrally mounted in the body by a streamlined spider. Standard valve sizes from ½ in. to 24 in. are available for pressures between 25 psig and 12,000 psig and for temperatures between −65°F and 400°F. Special models up to 72 in. and for more extreme operating conditions can be furnished in numerous alloys. This type of valve is said to be particularly suitable for automatic control, since the balanced piston-sleeve provides minimum hysteresis and fast response—as high as 120 cycles/sec in some systems. The manufacturer is the Bendix-Pacific Division of the Bendix Corporation.

Another new type of valve was displayed by Airmatic Valve Inc. of Cleveland, Ohio. This Tube-O-Matic valve employs an internal rubber sleeve which closes on internal annular seats when air or hydraulic pressure is applied outside the sleeve. At present, these valves are only obtainable in small sizes, designed for solenoid operation. Although pressure drop in these valves is appreciable, the simplicity of design and electrical operation are useful features.

One item strictly for process men was the ram valve, made by Strahman Valves Inc., of Florham Park, New Jersey, which has been designed to eliminate plugging problems when draining or sampling vessels and lines; it incorporates a long piston, which not only opens and closes a drain port in the valve body, but can be made to protrude several inches in the interior of a vessel, thereby breaking through deposited sludge and scale. Manual, pneumatic or motor-operated designs of this valve are available.

Flow Meters

Fischer & Porter Inc. demonstrated their recently introduced Magnarator variable-area flowmeter. This embodies an indicator-transmitter operated by a magnetic follower of ingenious design and is available for rates up to 100 gpm of liquid or 400 scfm of air. The transistorised F & P magnetic flowmeter was also shown. Schutte & Koerting Inc., of Cornwells Heights, Pa., displayed their latest magnetic and electronic alarm-rotameters, as well as their useful by-pass rotameters which can be used to measure large flows in horizontal lines. A well-built ring-balance flowmeter with optional electronic computation and transmission was shown by Hogan Chemicals & Controls Inc., of Pittsburgh, 30, Pa., who also demonstrated their latest cartridge-type inking system for chart recorders.

Nuclear and Electronically Operated Instruments

Several companies, such as the Nuclear Chicago Corporation of Des Plaines, Illinois, and The Ohmart Corporation, of Cincinnati, Ohio, exhibited a variety of radiation-type density and moisture gauges for process and field applications. The Nuclear-Chicago 500 series of instruments comprises gauges for continuously determining and controlling the densities of bulk materials, slurries and liquids, via the use of gamma-ray techniques. The water contents of bulk solids and liquids can also be determined, with automatic compensation for density variations. Analogue and digital control systems are available to provide process control, read-out information and integration with computer control as desired. The N-C d/M model is a portable density and moisture gauge suitable for surface or underground measurement in the field, and sells for about $1500.

Other recently introduced moisture gauges that were exhibited included the Aquatel made by Curtiss-Wright Inc., of Princeton, New Jersey, and the Model "W" analyser of Meeco Instruments, Hatboro, Pa. The Aquatel measures the A.C. conductivity of sheet or strip, with automatic compensation for capacitance, while the Model "W" instrument measures the moisture content of gas streams electrolytically down to limits below one part per million.

Alpha-radiation has been ingeniously adapted to the trace monitoring of toxic gases in the new "Billion-Aire" analyser made by Mine-Safety Appliances Inc., of Pittsburgh, 8, Pa. Operating in the parts-per-billion to parts-per-million range and using a few micrograms of radium as the emitter, many different gases and hydrocarbons can be measured, following sensitisation by pyrolysis or a simple chemical reaction.

General

In opposition to the numerous computer-controllers exhibited was the "K Logger" annunciator made by Keinath Instruments, of Columbus, 12, Ohio. This device continuously charts up to 400 variables on 100 separate frames in four colours (against a common time axis) on a single large sheet of paper mounted on a board, which also carries alarm lights and signals. It is claimed that not only is human control optimised to the highest degree by this recorder-annunciator, but the cost per recorded point is lower than that of any other logging system.

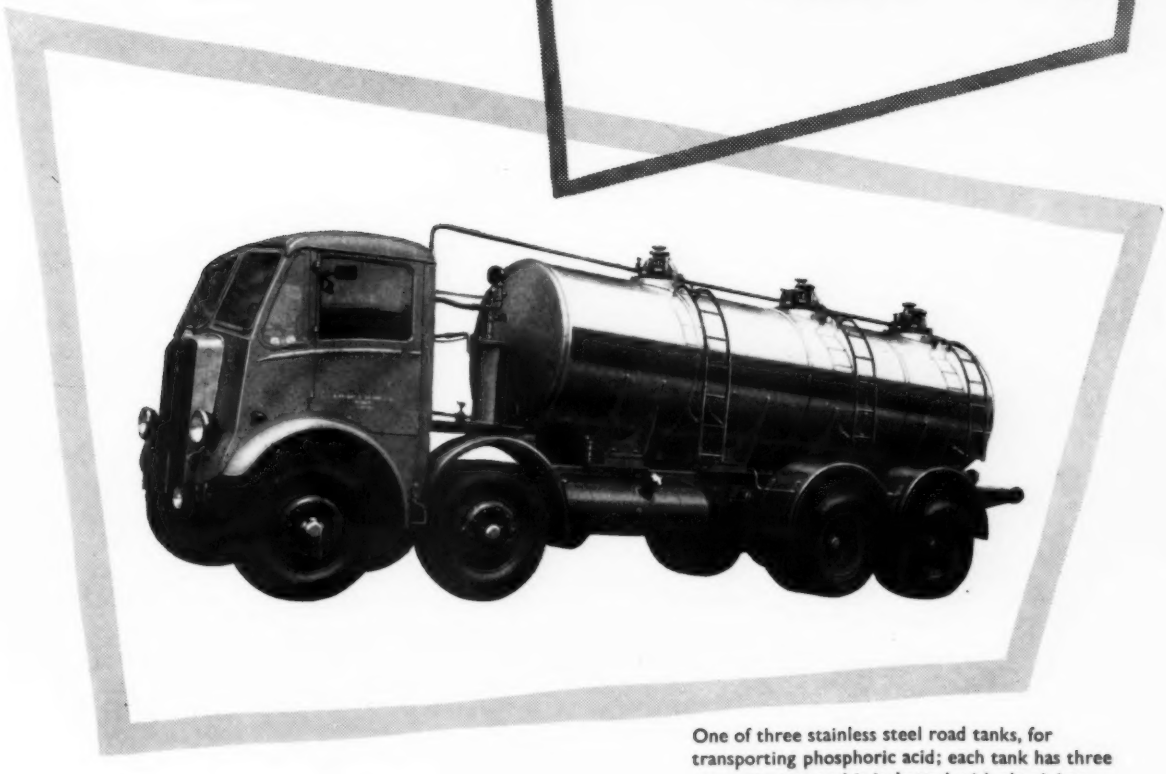
For the small plant or laboratory, Assembly Products Inc., of Chesterland, Ohio, offered their $98.00 Pak-A-Tool do-it-yourself automatic control kit. Another low-cost trend observed was the revived interest in temperature-sensitive paints and crayons offered by such firms as Tempil and Curtiss-Wright and which can be used for temperatures between 104°F and 2460°F.

These contrasted oddly with the latest radiation-type thermometers exhibited by Radiation Electronics Inc., of Chicago, 48, Illinois, and Toshiba, of Tokyo, Japan. For example, the R.E. Model TD1 has a temperature range of 100°F to 8000°F, a time constant of 2 milliseconds and a focusing range between 4 ft and infinity, yet is sufficiently rugged for plant use.

Not every budget, however, permits the use of such elegant equipment, and no doubt many process men perform miracles solely with the aid of a sagger or a "Tempilstick"

SPECIALISED FABRICATION

¾in. mild steel plate valve casing, weighing 4 tons; in two pieces, a cylinder and a cone; dia. 9ft. 7ins. tapering to 6ft. 2ins. by 10ft 4½ins. long.



One of three stainless steel road tanks, for transporting phosphoric acid; each tank has three compartments and is jacketted with aluminium.

These two examples are typical of the large range of fabricated productions produced by Widnes Foundry and Engineering Co. Ltd., who offer a comprehensive service to industry, both in fabrication and foundry work.

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W 48

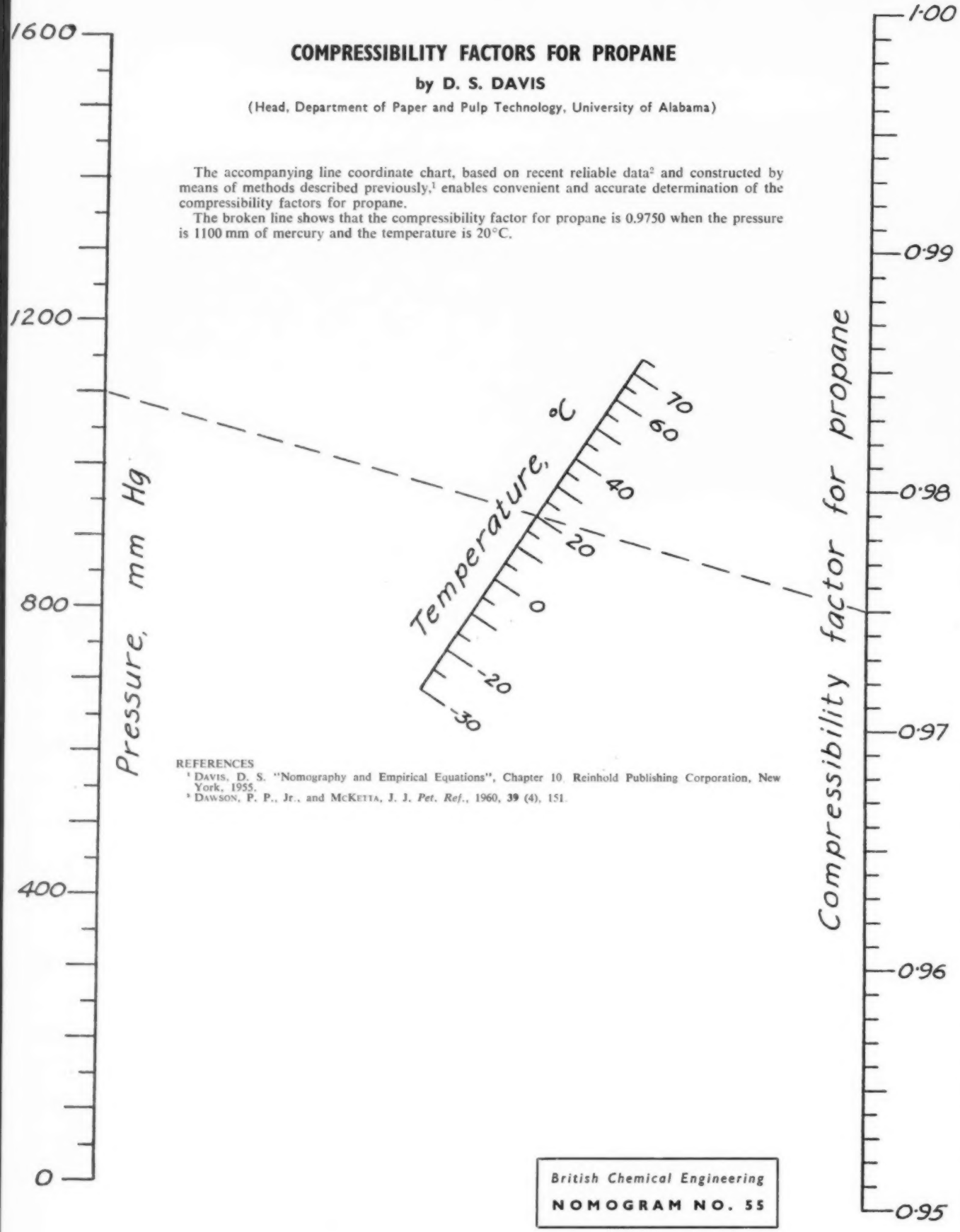
COMPRESSIBILITY FACTORS FOR PROPANE

by D. S. DAVIS

(Head, Department of Paper and Pulp Technology, University of Alabama)

The accompanying line coordinate chart, based on recent reliable data[2] and constructed by means of methods described previously,[1] enables convenient and accurate determination of the compressibility factors for propane.

The broken line shows that the compressibility factor for propane is 0.9750 when the pressure is 1100 mm of mercury and the temperature is 20°C.



REFERENCES

[1] DAVIS, D. S. "Nomography and Empirical Equations", Chapter 10. Reinhold Publishing Corporation, New York, 1955.

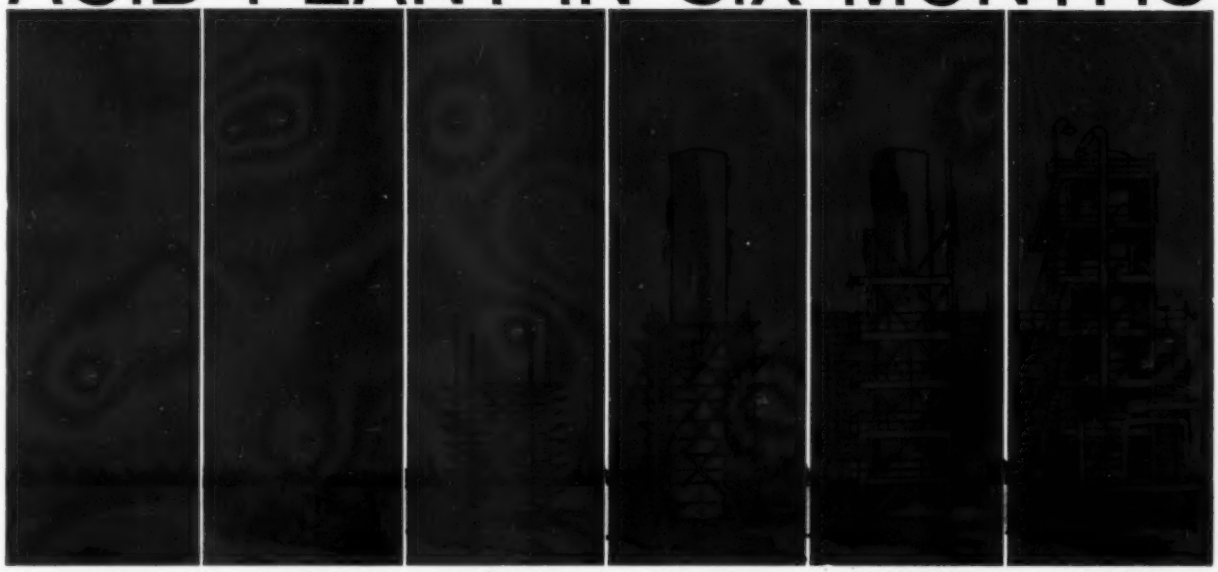
[2] DAWSON, P. P., Jr., and MCKETTA, J. J. *Pet. Ref.*, 1960, **39** (4), 151.

British Chemical Engineering

NOMOGRAM NO. 55

BCE 8905 for further information

CHEMICO BUILDS NITRIC ACID PLANT IN SIX MONTHS



It took just six months for Chemico to successfully complete a 120 ton per day nitric acid plant in Lawrence, Kansas. Until the client gave his final "go-ahead," not an hour of drafting or engineering had been done on the project—not a single piece of equipment had been placed on order. Yet, six months from that date, the plant finished its acceptance test run, producing at above rated capacity.

With 34 nitric acid plants in operation all over the world, and three more in the design stages at this very time, Chemico maintains its position of leadership in this field. In building plants to produce Ammonia, Urea, Nitric Acid, Acetylene, Methanol, Hydrogen, Sulfuric Acid and other chemical and petrochemical products, Chemico is setting new standards for the entire engineering industry.

This six month performance for a nitric acid plant follows closely the recent successful completion of an ammonia plant in ten months. It is not just the time factor alone which sets Chemico plants apart, however. Chemico clients know that they are buying efficient, economical, proven processes which assure ease of start-up and simple, safe operation. If you are considering building a new plant or enlarging present process facilities, let Chemico help you get the most for the capital you invest. Write for the General Bulletin which describes the wide range of Chemico's activities.

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RECENT CHEMICAL ENGINEERING THESES FOR HIGHER DEGREES*

Forced Convection Mass Transfer in Solid-liquid and Liquid-liquid Systems

by W. M. Topp (Ph.D., Manchester University)

Experimental data are presented for mass transfer experiments with solid-liquid and liquid-liquid systems. The apparatus used was a completely enclosed cylindrical cell of internal diameter 4 in., with the interface between two immiscible liquids restricted to a narrow annulus between circular baffles. Each phase, which was about 300 ml in volume, could be independently agitated by flat-paddle type stirrers over a wide range of stirring speeds without disruption of the interface.

In addition, solid dissolution studies have been carried out in two "half" cells, in which the dissolving solid replaced one of the liquid phases. Dissolution rates for one system, benzoic acid-water, were measured for a range of stirring speeds and from a comparison with previous similar work by JOHNSON and HUANG the general correlation for both "half" cells was presented as:

$$Sh = 0.043\ (Re)^{0.65}\ (Sc)^{0.5} \quad \ldots.(1)$$

Studies with three pairs of partially miscible liquids, in which one phase was always unstirred, showed that experimental film coefficients were of the order of twice as high as values predicted for the liquid-liquid case using Equation (1), and the ratio of observed to calculated coefficients was found to increase with Reynolds number.

The effect of a stationary gauze in the unstirred phase, very close to but not touching the interface, was observed visually to reduce interfacial turbulence due to stirring, but no decrease in transfer coefficients was found. The effect of presaturating the unstirred phase was also investigated; again no difference between the results of otherwise identical tests was observed.

An attempt to improve the existing empirical correlations for the prediction of individual coefficients was not successful as the dependence of coefficients on liquid properties and stirring rates was found to be more complicated than was at first thought.

Conflicting views have been expressed in the literature as to the importance of solute diffusivity in this type of stirred cell apparatus. In the present work experiments on the transfer of three solutes between two solvents under constant stirring conditions are described.

Overall coefficients calculated by the equation

$$\frac{1}{K_{ow}} = \frac{1}{k_w} + \frac{1}{Hk_s} \quad \ldots.(2)$$

where the individual coefficients k_w and k_s were determined experimentally, are compared with experimental values.

The results of the present work, together with a detailed examination of the experimental data of GORDON and SHERWOOD, leave the question of solute diffusivity unresolved.

The effect of solute concentration on transfer rates has been examined for two systems which, according to the literature, show appreciable interfacial turbulence.

The system studies were acetone transferring between carbon tetrachloride and water and between toluene and water. Two initial concentration levels were used, 2 and 7 gm/100 ml, and the stirring conditions were such that results were compared to similar experiments of LEWIS, who worked with concentrations of approximately 4 gm/100 ml.

Increase of coefficients with concentration was found in three of the four directions of transfer, one equivalent case agreeing with the findings of CONNOLLY[1] using natural convection processes. However, in the case of acetone transfer from water to toluene, increase of coefficients as observed by this author was not found.

REFERENCE

[1] CONNOLLY, Ph.D. Thesis, May 1958.

The Separation of Mineral Oils by Chromatography

by M. J. Ray (Ph.D., Manchester University)

The work presented in this thesis forms part of a research project into the constitution and carcinogenic activity of mineral oils. The oil fractions being studied are in the boiling range 350-410°C at atmospheric pressure.

The preliminary preparation of oil fractions by distillation and solvent extraction is reviewed, and reasons given for the use of further methods of fractionation.

The aim of the work reported was to separate narrow boiling range, aromatic extract oils into chemically homogeneous fractions. Liquid - solid adsorption chromatography was the method selected.

Small-scale experiments using silica gel and alumina as the adsorbent, with iso-octane as eluent, and benzene followed by methanol as displacers, were carried out to obtain a separation of the oils into paraffinic plus naphthenic, aromatic and residual hydrocarbon fractions. The data collected from the small column operations was used to design a semi-pilot plant scale column, constructed of glass, with brass ancillary equipment. After erection and testing, the column was used for the fractionation of the oils to produce fractions in the quantities required for biological and chemical testing.

As a result of the biological testing, further fractionation of the aromatic hydrocarbon portion was required. This was attempted on a small scale using adsorption chromatography with alumina as the adsorbent, iso-octanes as eluent, and benzene followed by methanol as displacers. Separation of the oil was possible using this method, and the procedure was repeated with the semi-pilot plant column.

Comparison of the separations obtained with the small-scale and semi-pilot plant scale units exposed insufficiencies of the latter with respect to its efficiency for the quantities of oil it was desired to separate. To improve the fractionation of the oils, the design of a chromatographic column, constructed of stainless steel, with a higher length/diameter ratio was considered.

In order to put forward the full specifications for such a column, certain problems affecting the design required investigation. The effect of adsorbed water on the activity of an adsorbent, and possible drying and regeneration were two problems which were studied, as they would reveal the necessity of providing the column with heating-jackets in order that the adsorbents could be conditioned before use.

The first problem was studied with the aid of model binary mixtures, and the latter by treatment of the adsorbents with methanol, followed by activation with a stream of hot nitrogen.

Coking Mechanism of Bituminous Coals

by C. P. Chamberlain (Ph.D., Manchester University)

A number of coals of known bituminous character were studied for the yields of adsorbed oil through the plastic temperature range and compared with results from non-bituminous coals. Under the same conditions of heating, plasticity, swelling, and volatile matter determinations were carried out in the same coals in order to compare the results with those of the oil adsorbed. From the results obtained it was found possible to advance a hypothesis for coal-coke change based broadly on the available plasticity theories.

There was, however, evidence which supported a later idea put on a quantitative basis by CHERMIN and VAN KREVELEN[1] which suggests that the coal changed to coke through an unstable liquid phase which "recondensed" after formation.

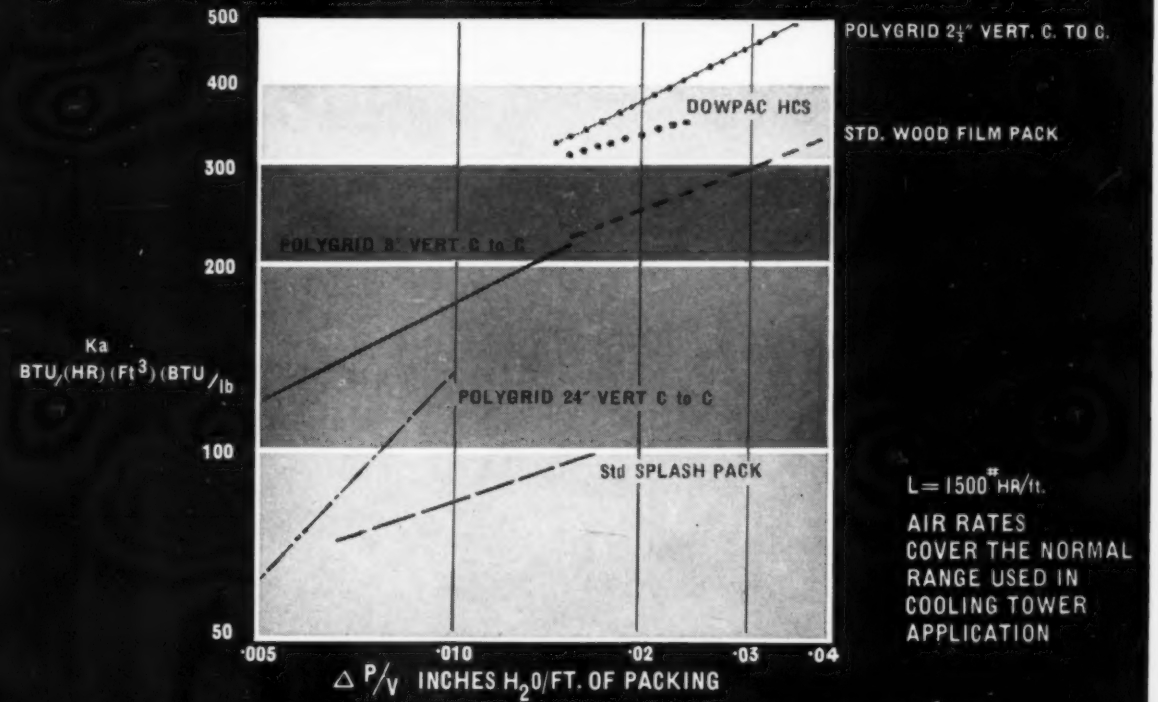
REFERENCE

[1] CHERMIN and VAN KREVELEN, *Fuel*, 1957, **36**, 85-103.

* Valuable information may be lying fallow in many cases in theses presented for higher degrees in universities and not published in journals. *British Chemical Engineering* is therefore arranging to publish a number of synopses of such theses for the information of our readers, as an occasional feature.

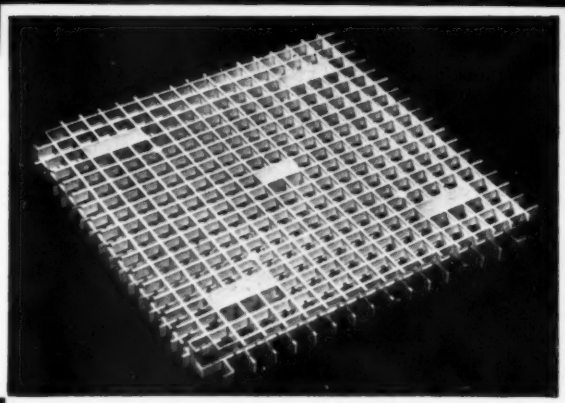
IMPROVED COOLING PERFORMANCE BY

POLYGRID PACKING



Performance of Polygrid in Counterflo Cooling Tower

Polygrid—a new high-efficiency non-corrosive plastic packing has been performance-proved in more than 100 cooling tower installations. It is used exclusively in Head Wrightson Fluor Counterflo towers. Head Wrightson Processes Ltd. will also install it in established mechanical or natural draught towers of all types and makes to increase their efficiency and performance.



Polygrid is a moulded unit of two inch squares. Units, staggered in layers, break hot water into droplets as it cascades through the tower. Available in high impact polystyrene for resistance to water, acids, salts and alkalis, and in high density polyethylene for cooling water contaminated by hydrocarbons.

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P.3542

PLANT EQUIPMENT NEWS

CD-48 Glassed-steel Dryer-blender

The Pfaudler "CD 48" dryer-blender was exhibited by Enamelled Metal Products Corp. (1933) Ltd. at the Olympia Corrosion Exhibition, 1960. Highly corrosive materials can be dried and blended in this unit to produce a homogeneous product with great saving in operating time and costs. The inner tank is lined with acid/alkali-resisting glass and will withstand full vacuum, or pressures up to 20 psi. The mild-steel jacket will accommodate pressures up to 40 psi with full

vacuum in the inner tank. There is an electric motor and gear drive with variable speed available as an extra. The basic inside diameter is 4 ft; the total capacity is 32 cu ft with a working capacity of 21 cu ft; the heated area is 48 sq ft and the drying speed 12.5 rpm. **The Balfour Group of Companies, Artillery House, Artillery Row, S.W.1.**

BCE 8951 for further information

New Corrosion-resistant Sprayed PVC Coating

The availability in this country of a new corrosion-resistant sprayed PVC coating which has an unrivalled range of application is announced by BTR Industries Ltd as an addition to their "Synco" range of corrosion-resistant materials.

An outstanding feature of this PVC coating is its wide potential application in the chemical industry—its resistant properties range from alkalis to oxidising acids, from fatty acids and their esters to petroleum hydrocarbons and alcohols.

This PVC coating, which can be applied either in BTR's factories or on site, is diffusion proof and can be employed under high mechanical stresses at operating temperatures up to 70°C (158°F). Added advantages are its abrasion resistance and impermeability. **BTR Industries Ltd., Herga House, Vincent Square, London, S.W.1.**

BCE 8952 for further information

New Silicone Products from I.C.I.

General-purpose, high-strength, fully-compounded stocks, with superior mechanical properties to earlier general-purpose stocks, are offered in the E 313 class of I.C.I. silicone rubbers. There are four members of the E 313 class—50 B.S., 60 B.S., 70 B.S. and 80 B.S. rubbers—designated by the appropriate numerical suffix.

The new solvent-based silicone product M 492, intended for water-repellency treatment of both textiles and leather, is particularly recommended for heavy fabrics. Besides imparting a high degree of water-repellency, M 492 has the significant advantage of being air drying, thus eliminating the high-temperature backing process that is usually necessary with silicone treatments. M 492 is easily applied by brushing, dipping or spraying and it is well suited for the treatment of canvas, awnings, tarpaulins and leather.

Three development products are also made available. The first, DP 115, is a silicone resin with great promise as adhesive and binding material. Supplied as a high solids content solution in acetone, the product, when applied, rapidly dries in air to give a tack-free film that cures on heating to give a rigid bond that is heat-stable and moisture-resistant.

Recommended applications include its use as an adhesive for bonding silicone resin/glass cloth laminates to each other and to metal; as a moisture-proof coating for resistors and glass or asbestos served wire.

A second development product, DP 163, is a silicone resin for semi-permanent release coatings on metal surfaces. This resin, dissolved in an aromatic solvent, can be applied by spraying, brushing or dipping. After curing at 200°C it gives a hard, smooth coating with admirable release qualities and long life, even at temperatures of 200-250°C.

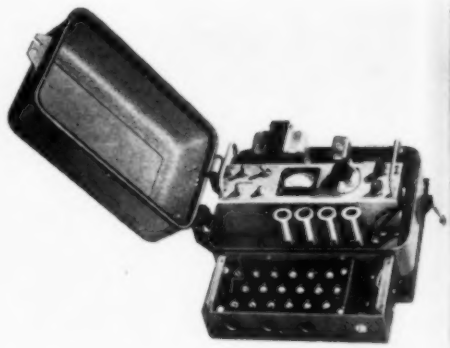
The third product, DP 137, formulated for the manufacture of expanded microcellular rubber, is neutral in colour but may be pigmented as desired. It can be used at temperatures from −80°C to plus 250°C. **I.C.I. Ltd., nearest sales office, or Imperial Chemical House, Millbank, London, S.W.1.**

BCE 8953 for further information

Automatic Weight Control

This entirely new type of electronic weighing equipment is for use in almost any industry in which requirements call for the weighing and control of plants handling food, animal feedingstuffs, rubber, cement, chemicals, glass and many other products.

The type LC4 and LC5 trip point controllers give reliable control under the most arduous conditions. The load cells can be safely used in very wet conditions



or even submerged, and flameproof equipment can be supplied as standard.

No mechanical accessories whatsoever are used in these indicators and in this way any failure of the moving coil type instrument does not and cannot cause control failure.

These equipments are intended to provide a control function when a pre-set weight is reached. Industrial loads of any size in the range 20 lb up to 2000 tons may be dealt with, and it is of interest primarily in handling bulk materials or containers.

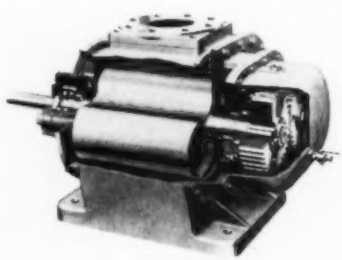
For example, they may be used to control the filling and emptying processes of hoppers and tanks by weight; for automatic enforcement of safe loading limits with cranes and hoists; for automatic prevention of over-stressing in chuck tightening-down operations; for tension control in paper, textile and rope handling processes; for control of blending processes by weight in the chemical and food industries; and numerous other control operations. **Elcontrol Ltd., Wilbury Way, Hitchen, Herts.**

BCE 8954 for further information

Holmes-Connersville Positive Air Blowers

Recent modifications to the range of type RBS Holmes-Connersville positive air blowers have resulted in a number of operating advantages, including improved performance.

The impellers and shafts are now of fabricated construction in steel, making it possible to use much larger shafts and



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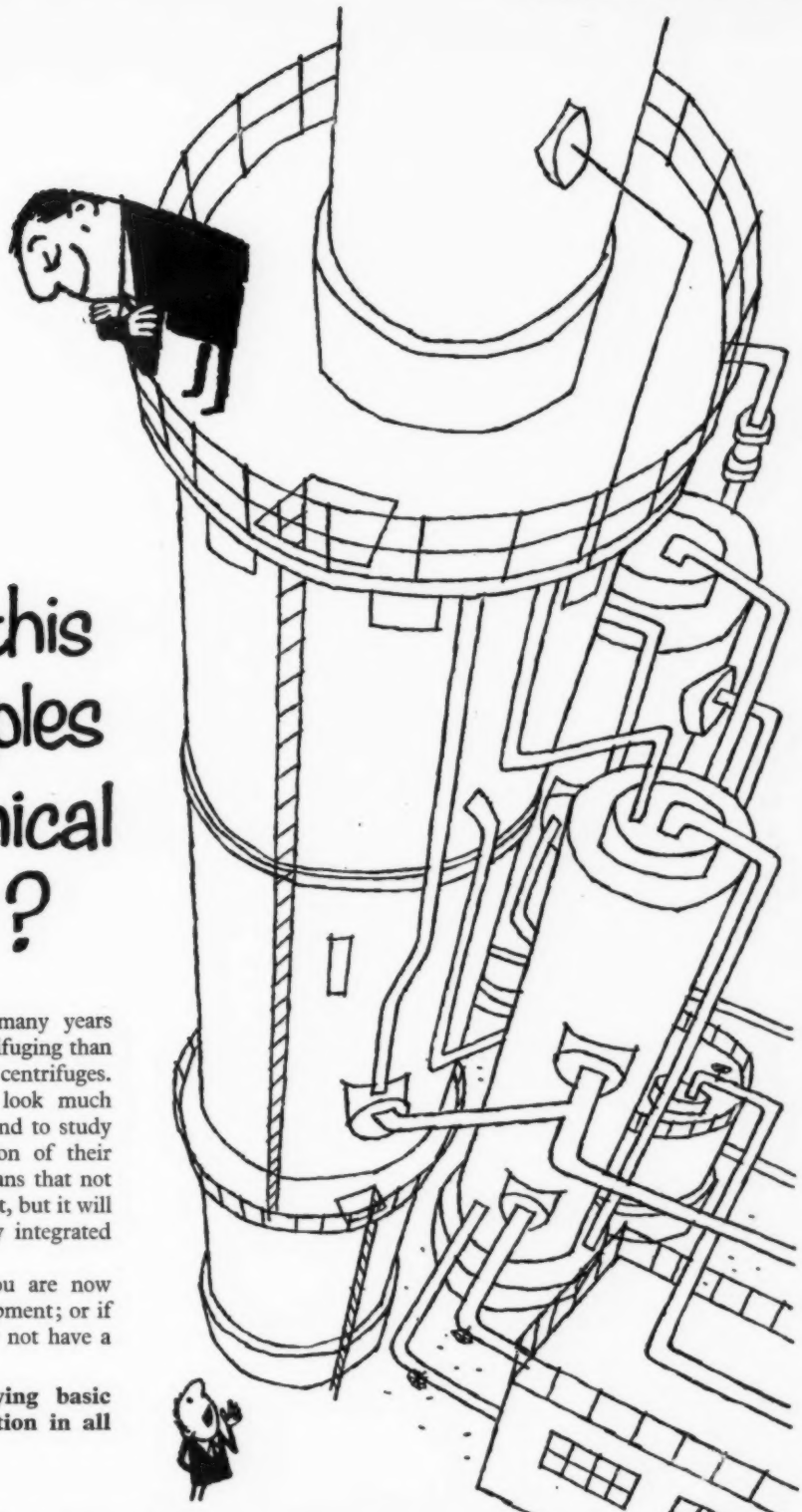
BCE 8907 for further information



Hi! What's this about Sharples being Chemical Engineers ?

IT'S A FACT. Sharples have for many years realised that there was more in centrifuging than just building a complete range of centrifuges. Their policy has always been to look much further than the centrifuging step, and to study the process as a whole. Application of their chemical engineering knowledge means that not only will the separational step be right, but it will be a unit operation that is correctly integrated with the process.

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PLANT EQUIPMENT NEWS

bearings which increase the allowable pressure loading on each size of machine. The maximum pressure for some sizes has been increased from 10-15 psi.

Another important advantage is that these blowers are constructed with air gaps which completely isolate the bearing housings and gears from the casing. This ensures that under no circumstances, even in the event of an oil-seal failure, is it possible for air passing through the blower to become contaminated with oil or oil vapours.

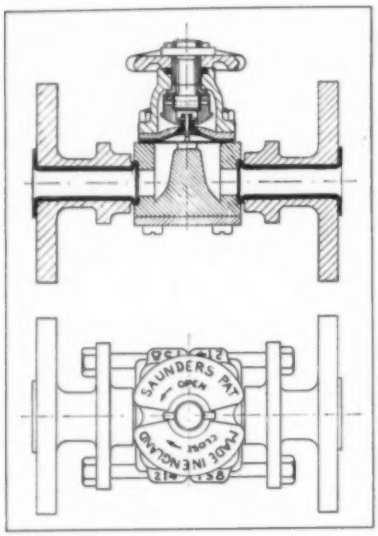
When handling gases other than air, type RBS blowers can be fitted with mechanical shaft seals which are considerably more efficient than the stuffing box and gland previously used. The mechanical shaft seal is much more compact and it requires little or no attention. **W. C. Holmes & Co. Ltd., Turnbridge, Huddersfield.**

BCE 8955 for further information

Diaphragm Valves

On show at the recent Corrosion and Metal Finishing Exhibition at Olympia, London, were some of the latest designs of remote-controlled valves manufactured by the Saunders Valve Co. Ltd.

New developments include a rubber-lined non-return valve and a solid PTFE valve. These are of particular interest for metal plating plants.

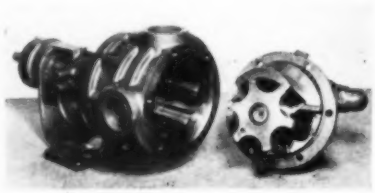


A wide range of lined valves—using rubbers such as neoprene and ebonite, metals such as lead or titanium, and plastics such as nylon or polythene—are now available. The range of diaphragms is so comprehensive that virtually all fluids can now be controlled. **Saunders Valve Co. Ltd., Cwmbran, Monmouthshire.**

BCE 8956 for further information

Internal Gear Rotary Pumps

A new versatile range of robust, self-priming, internal gear rotary pumps for delivering a steady non-pulsating flow are now available. There are models to handle capacities of from 3-250 gal/min at pressures up to 100 psi.



The flow of liquid on the delivery side is smooth and without pulsation and the rate of flow is virtually proportional to pump speed, irrespective of pressure. They have the ability to pull a high vacuum on the suction side which is an important feature of the pump, as its self-priming ability enables liquids rapidly to be lifted from below pump level. A wide range of industrial liquids can be handled and the pumps can be supplied in all-iron, iron and bronze or all-bronze. They can, if required, be supplied steam-jacketed for maintaining the temperature of pre-heated liquids. **Wayne Tank & Pump Co. Ltd., Western Road, Bracknell, Berks.**

BCE 8957 for further information

Variable Speed Motor Gears

A range of variable speed motor gears made by Crofts (Engineers) Ltd. is available with speed ratios of from 10:1 to 2:1 and will provide up to 20 hp.

There are two basic types in the range: the Universal, which is made in five versions known by the initials U, UR, UFM, UW and URW, and the Vertical, which is sold in two versions, the V and V1.

With both models, the variable speed drive assembly is supported on integral feet. With all the Universal models, the position of the variable speed drive can be arranged in a wide variety of positions in relation to the reduction gear to suit the layout of the plant. With types UW and URW the output shaft may be fitted in a vertical position, either up or down, and UFM can be fitted with this shaft in a downward position.

The variable speed drive assembly is combined with either a "Ritespeed" spur gear or a "Par-o-mount" worm gear.

The motors are of the squirrel cage induction type and are totally enclosed. A minimum of vibration occurs, as a special shaft extension is fitted to provide rigid support for the driving cones.

The variable speed drive consists of driving cones keyed to the motor shaft. A speed control mechanism, operated by a handwheel, actuates the sliding cone; it is contained in a semi-steel housing which is flanged to the casing containing the driving and driven cones and belt. The driven cones are spring loaded and keyed to the variable speed shaft.

The motor is air cooled, air being taken in by fins cast integral with the cones through an air inlet in the belt housing enclosing the spring.

A speed control mechanism gives positive movement of the drive cones, while the spring-loaded driven cones automatically adjust belt tension, thus ensuring immediate speed changes.

The speed control handwheel has a large dial calibrated in either 12 or 24 divisions. A red pointer makes a complete revolution of the dial as the black pointer moves across one division. An electronic tachometer can be fitted if extreme accuracy is required and dials giving calibrations in rpm or fpm can also be supplied.

The "Par-o-mount" worm gear has a casing of one-piece construction with feet cast integrally. It has a large surface to provide maximum heat dissipation. An oil filler breather and level plugs are fitted.

In applications where the load might run back when the power supply is cut off, a high speed roller backstop can be fitted to the wormshaft on gears 3 to 5-in. centres. This backstop can be fitted to suit either direction of rotation.

The gears of the "Ritespeed" reduction gear are precision generated, and to reduce power losses to a minimum special care is taken to ensure correct tooth form and a smooth surface finish. Dual-purpose bearings are fitted for vertical shaft arrangements or where thrust loads occur.

For applications involving high inertia starting, the variable-speed motor gears can be used in combination with Crofts centrifugal multi-disc clutch. The clutch enables the motor to accelerate up 75-80% of full speed before taking up the load, thus resulting in a very smooth acceleration of the load.

For conveyors and similar applications where frequent starting and stopping is necessary, the Crofts electrically released magnetic brake can be incorporated in the motor gear.

It applies a braking torque to the variable speed shaft; when the motor is stopped the brake inertia is overcome directly through the shaft.

The brake is of the friction disc type and has dry plates. Braking torque is applied by means of springs, fitted in the coil housing, acting through a pressure plate. The brake is released when the power supply is switched on. Six sizes of brake are available. **Crofts (Engineers) Ltd., Bradford, 3.**

BCE 8958 for further information

Joy-Hazemag Crusher

The Joy-Hazemag crusher, originating from Germany, is manufactured in four series, each of which comprises a number of models of different capacities: (a) heavy-duty series for hard rocks, slags and aggregates; (b) standard duty series for primary and secondary crushing of limestones, friables, coal, salt, etc.; (c) medium duty series for secondary and tertiary crushing of limestone, coal, etc.; (d) fast runners for fine crushing and fibrising. The above series covers a range of capacities up to 500 tons hr.

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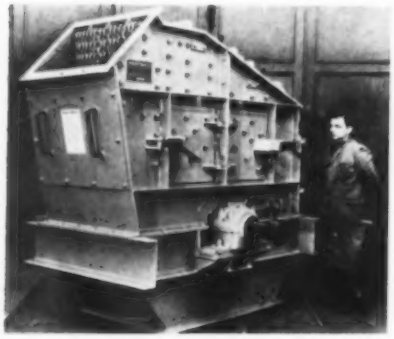


The crusher gives a positive degree of selective crushing. When a mixed material having elements of different impact strength is fed to the Hazemag, the material of low strength is subject to finer crushing than that of high strength. Two easily separated products are thus obtained, the finer being rich in the low-impact-strength material, and the coarser rich in the high-impact-strength.

It can be varied to produce a particularly fine — or coarse — product, as required. In certain cases reduction ratios of more than 100:1 are possible. Ratios of 40:1 are normal.

As the Hazemag is relatively small and requires only light foundations, installation cost is low. Maintenance costs due to wear are also low because of the relatively low rotor speeds used. By reason of its gravity-hung impact plates, the Hazemag is immune to damage caused by the accidental entry of foreign materials. **Joy-Sullivan Ltd., Greenock, Scotland.**

BCE 8959 for further information

Novel High-pressure Valves

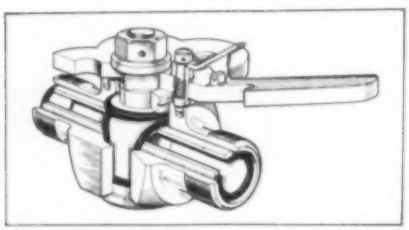
The phenomenal sealing properties of standard "O" rings have been applied to rotary valve sealings, making the Orseal range of high-pressure valves suitable for use under vacuum, or at pressures up to at least 3500 psi.

Manufactured from forged steel, they are suitable as shut-off or flow control valves in high-pressure air, oil and water circuits, and in telemotor systems.

The range at present available is as follows: up to 1¼ in. normal size in forged steel for working pressures of 3500 psi; up to 2-in. bore in gunmetal for pressures of 500 psi; and from 3-8 in. bore in cast iron for working pressures of 250 psi.

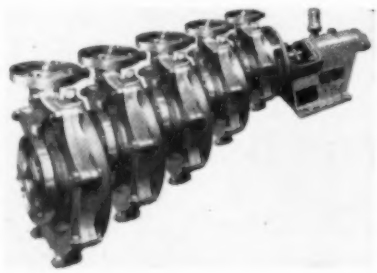
The advantages claimed for this valve are bubble tight under vacuum and pressure; smooth full-bore passage; no lubrication except in special cases; simple construction due to the use of a cylindrical plug; and negligible maintenance (four new "O" rings can be fitted in one minute without removing the valve from the line). **Peckett & Sons Ltd., Atlas Works, St. George, Bristol, 5.**

BCE 8960for further information



Stainless-steel Chemical Pumps

The demand for stainless steel by engineers in the chemical, process and food industries has led to the development of a range of Tangye-Smart stainless-steel "C"-type chemical pumps. The range gives a high degree of interchangeability and flexibility. The pumps have capacities of from 2-350 Imp. gal/min and develop heads of from 10-210 ft. To provide this wide range of duties, only one bearing bracket was necessary and this accommodates five different hydraulic sections (illustrated). The standard material for the casing, the impeller, and the shaft and gland is BS 1632 stainless steel of the

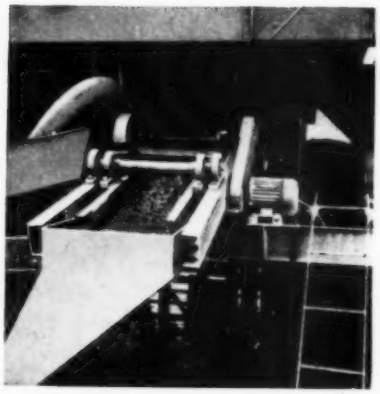


well-known 18/8/3 chrome nickel molybdenum because of its well-known resistance to corrosion. The satisfactory sealing of the pump is essential on chemical applications, and so a deep stuffing box has been designed to accommodate either soft packing or a mechanical seal without modification in either case. Double mechanical seals can be fitted when required. The standard "C"-type chemical pump will handle liquids satisfactorily at temperatures up to 230°F. **Tangyes Ltd., Cornwall Works, Smethwick, Birmingham.**

BCE 8961 for further information

Resiliently-mounted Vibratory Screen

This is a light screen for use in the ceramics industry, but should find many applications in the quarrying, mining, gas and, when made from stainless steel, in the chemical industry. Many new design features are incorporated, including the mounting of the entire screen body in bonded rubber bushes. All sizes up to 10 ft × 4 ft are available with a maximum power requirement of 3 hp. The amplitude of vibration is variable and, where required, models can be supplied arranged for double-deck screening and also for mobility.



The screen is readily adapted for deck heating which prevents the moisture content of fine materials from causing binding. It effectively handles fine clay with a 10% moisture content. **Saxon Engineering Co. Ltd., Fenton, Stoke-on-Trent.**

BCE 8962 for further information

Electronic Check-weighing Systems for Mass-production Lines

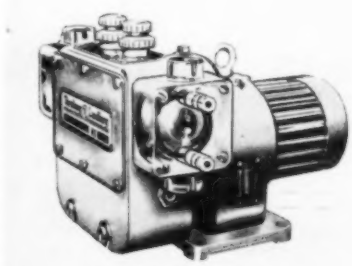
An electronic high-speed check-weigher is used in mass-production lines of manufacturers whose goods are sold by weight in cans, packets, bottles or other containers. A typical installation is capable of check-weighing cans at speeds up to a maximum of 200 a minute. The weighing system, which has passed Board of Trade tests for automatic check-weighing machines, can maintain an accuracy of ±½% of the set level. The standard machine handles cans up to 3 in. diameter and 18 oz. weight. It takes up very little floor space: 36 in. × 28 in. for the machine itself, with 22 in. × 12 in. for the electronic control unit. The conveyor level is adjustable over a height of 34-38 in. from ground level. Cans are delivered to the machine on a PVC cotton-faced belt via a starwheel infeed.

The machine operates without an attendant. A drive cut-out device is incorporated, together with visible and audible alarms, in case a jam should occur as a result of distorted or bent cans. **Elliott-Automation Ltd., 34 Portland Place, London, W.1.**

BCE 8963 for further information

Diaphragm-type Liquid Feeder

The Tolu feeder now available in England for the first time is widely used for feeding under pressure liquids of various kinds. The feeder is available in



When did *you* last see a Dutch interior? Never mind! The point is that there's an art to protecting the interiors of tanks. And Ensecote has it. *Any* size of tank. *Any* sort of liquid practically. Ensecote protective linings are easily cleaned and sterilized; completely odourless, tasteless, and economical to install (larger vessels can be lined on the spot). Ensecote protective linings add years to a tank's life.

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PLANT EQUIPMENT NEWS

single or double units, the capacity of each unit being from ½-7 gal/hr. The flow can be varied within close limits while the pump is running and each unit is entirely independent. Plexiglass housings and stainless-steel parts are standard, but other materials are available for special applications. Maximum working pressure is 70 psi. **Neldco Processes Ltd., Crossway House, Bracknell, Berks.**

BCE 8964 for further information

Russell Lifting and Tipping Machine

This unit has been developed to meet the need for more rapid handling of all types of materials by eliminating the manhandling of them. It is a simple and reliable machine for lifting and emptying all types of containers weighing up to 10 cwt. The containers can be tipped so as to empty the contents into a hopper, truck, mixer or other receptacle. This machine, known as the "Hi-Tip", has a minimum height of lift of 4 ft 6 in. An interesting feature is the fact that vertical sections can be added to increase this dimension to any height desired.

It is fabricated of ¼-in. mild steel of all-welded construction and consists of a base, a top unit and centre sections. The base, which for the standard machine occupies an area of only 3 ft × 4 ft 6 in., houses the electrical equipment, control mechanism, main drive and chain compensating device, all the mechanical parts being adequately protected.

The top unit contains the actuating cam guides for the tipping action, and the centre sections, which can be added or removed to alter the height of lift, include the appropriate lengths of guide rails. The machine is powered by an electric motor with a self-contained braking unit.

The start and return operations are actuated manually, but automatic sequence control can be provided if required, the emptying time being controlled by a variable time switch. The speed of lift is 30 ft/min and the standard tipping angle is 30° from the vertical. The cradle can be adapted to take any particular type of containers such as drums, barrels, kegs, skips, trolleys, vats, bowls, sacks, etc., the chute being shaped to suit the material being handled.

It is suitable for continuous 24-hr operation. It requires virtually no maintenance and is foolproof in use. It can be provided in a portable form if required. **Russell Constructions Ltd., Russell House, Adam Street, London, W.C.2.**

BCE 8965 for further information

Safety Solvent for Industrial Cleaning

A recently-announced cold cleaning solvent known as Chlorothene NU may be used in wipe, dip, spray and slush cleaning operations. It is roughly 30% dearer than carbon tetrachloride, but has low toxicity, no flash point and is quick drying, properties which make it suitable for several industrial metal cleaning applications.

The material is an improved inhibited grade of 1,1,1-trichloroethane (methyl chloroform), one of the least toxic chlorinated solvents and is manufactured by The Dow Chemical Co.

According to the H.M. Stationery Office booklet, "Toxic Substances in Factory Atmospheres", the permissible concentrations of carbon tetrachloride is only 25 p.p.m., but that for 1,1,1-trichloroethane is 500 p.p.m. British agents are **Penetone-Paripan Ltd., Egham, Surrey.**

BCE 8966 for further information

New Alloy Steel for Storage and handling of Liquids at Very Low Temperatures

It is known that many steels, although tough and strong at room temperatures, become excessively brittle when cooled to sub-zero temperatures. It is also known that the presence of nickel greatly improves the toughness of steels down to temperatures as low as −200°.

The rapid increase in the use of liquefied gases like oxygen, nitrogen and methane, involving service temperatures of the order of −200°C, has quickly focused attention upon the need for materials for handling them with safety and economy.

The newly developed 9% nickel alloy steel has passed all the laboratory tests and a practical demonstration of its suitability by three companies in the U.S.A.

Tonnage oxygen plants are being installed in increasing numbers near steelworks and other industrial plants and there is a promising market underlying the liquefaction and sale of some of the methane flared-off and wasted at oil and petroleum fields throughout the world. The volume of this gas when liquefied at −157°C is reduced by 600 times and transportation in special tankers for very long distances, for example, the U.S.A. to Europe, becomes an attractive proposition. The economics of the liquid-gas market demand that the tankers must be built from a safe and relatively low-cost material which is commercially available and readily welded. The ability of 9% nickel steel to meet these requirements has now been demonstrated. **The Mond Nickel Co. Ltd., Thames House, Millbank, London, S.W.1.**

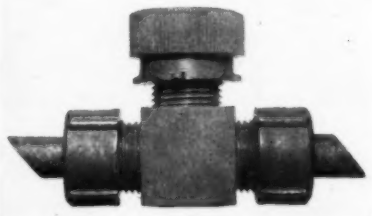
BCE 8967 for further information

All-plastic Needle Valve

A new needle valve constructed from styrene-butadiene acrylonitrile blend is now available in the following sizes:

¼ in. o.d., $\frac{5}{32}$ in. i.d.
$\frac{5}{16}$ in. o.d., ¼ in. i.d.
⅜ in. o.d., ¼ in. i.d.

It is being manufactured by Barflo Ltd. primarily for use with Wade couplings. It is recommended for use with fluids at 0-300 psi and gases at 0-100 psi. Each valve is designed with the "P"-type joint in "All-Plastic", with spigot support for the



tubing and knurled coupling nuts for hand tightening.

The feature of its design is its finger-tip control, no undue pressure being required to obtain a firm seating. **Wade Couplings Ltd., 270 High Road, Ilford, Essex.**

BCE 8968 for further information

Combination Vacuum Source

A number of advantages attend the use of combined water-ring vacuum pumps and water curtain condensers, such as the much reduced space requirement, low cost of erection and first cost. Further, the withdrawal of air and water by different pumps allows either to function with greater efficiency.

Burckhardt, already well known as makers of reciprocating wet air pumps and barometric condensers, now offer a wide range of combination water-ring pump condenser units. These have either one or two stages for the mechanical pump capable of vacua up to 40 mm or 25 mm Hg abs respectively. The single-stage units at their lowest attainable absolute pressure

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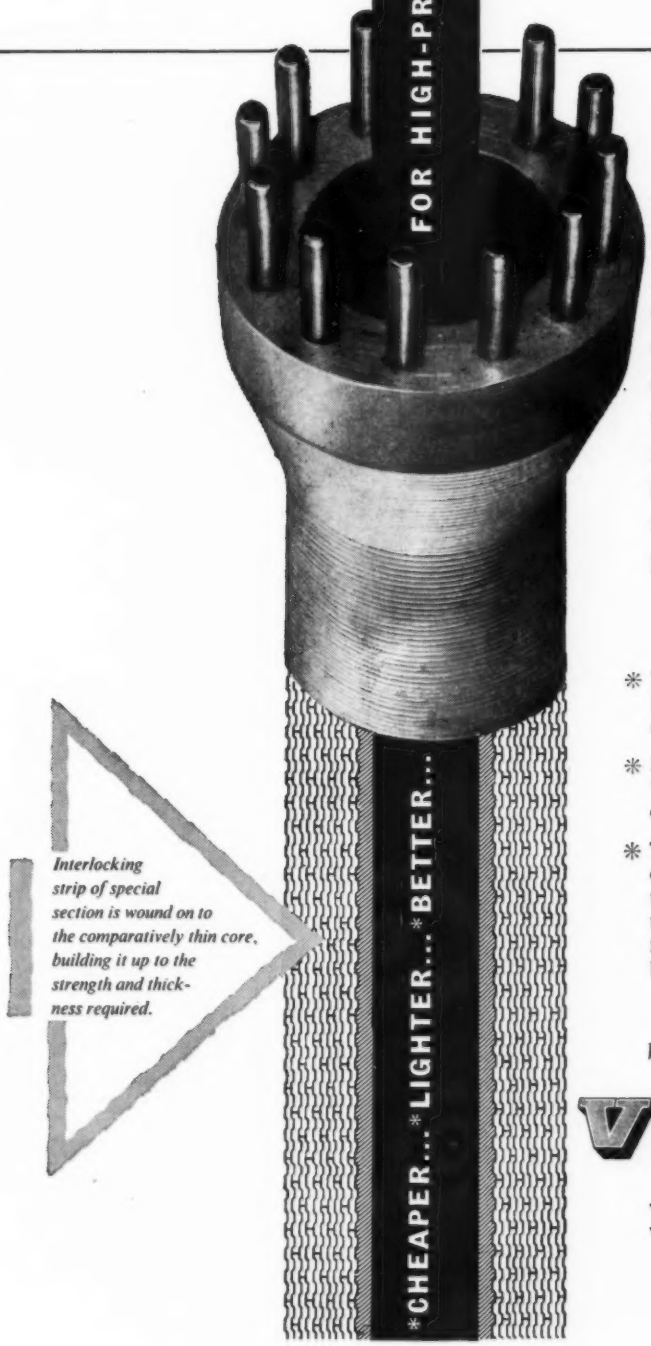
Strip-wound construction?

FOR HIGH-PRESSURE VESSELS



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Interlocking strip of special section is wound on to the comparatively thin core, building it up to the strength and thickness required.

The modern technique of Strip-Winding in High Pressure Vessel manufacture provides important advantages to those engaged in the design and construction of specialised plants where large volumes are to be accommodated at high pressures. In the chemical, hydraulic, research, oil and petroleum fields there are many applications for which this method of construction has already proved eminently satisfactory.

* Where corrosive liquids or gases are to be handled, only the core tube need be made from stainless steel or any other special material.
* For the larger sizes of cylinder, Strip-Wound Vessels are lighter than those manufactured by existing methods.
* The quality of the final vessel wall is rigidly controlled at all stages of construction irrespective of the number of layers involved because the small cross-sectional area of the strip makes for easy examination and proving of the material before winding on to the core.

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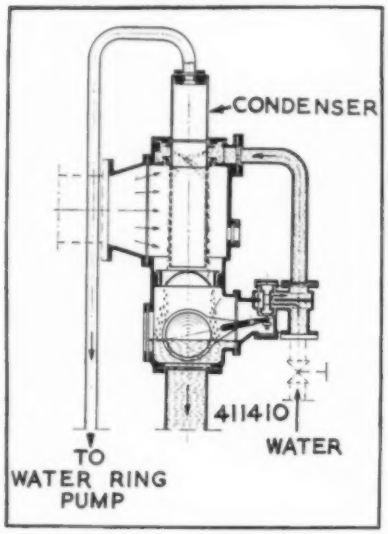
PLANT EQUIPMENT NEWS



(40 mm Hg abs) will, given cooling water at 15°C, condense 60-2020 kg/h of steam. Air displacement of the water-ring pumps varies from 55-700 m³/h.

In the case of the two-stage units, the condensable quantity of steam ranges from 54-755 kg/h and the air quantity at 25 mm Hg abs varies from approximately 89-650 m³/h. Cooling water requirements in the case of the single-stage units are 2.5-82 m³/h, while for the two-stage units, at the vacua stated, the figures are 4.5-62 m³/h.

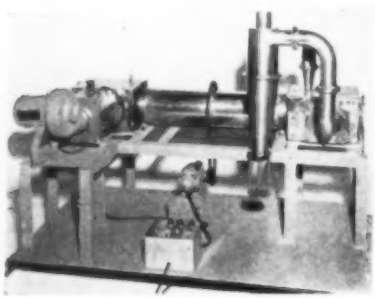
Other components of the unit include a centrifugal pump for discharging condensed and cooling water, an automatic valve for controlling the level in the condenser discharge tube and an inspection window on the curtain condenser to allow its operation to be inspected.

If required, all the parts can be supplied in special materials including 18/8/2.5 Mo stainless steel. **The Burckhardt Engineering Works, Basle.**

BCE 8969 for further information

Bench-scale Drier

A new bench-scale rotary drier is designed to provide a rapid and inexpensive means of determining the effect of drying variables on the quality of various products. Its design permits the investigation of parallel or counterflow continuous drying processes, and it is easily converted to a louvre-type unit, thus making it possible to evaluate rotary driers on a bench scale.



Standard units consist of chain-driven tube drier, pressure blower, electric air heater and cyclone dust collector. A manually operated feeder, various types of internal conveying flights and a discharge receiver are also included. Sight glasses allow visual observation of the drying process.

The drier consists of a stainless-steel cylinder, 24 in. long and 4 in. o.d., rotated by a gear-head motor and chain-and-sprocket drive; readily interchangeable sprockets provide two-speed adjustment. The cylinder is covered with 1 in. of insulation and its slope can be changed to permit adjustment of retention time. Eight conveying flights are supplied, and as many of these as desired can be used to provide various lifting and air-flow patterns within the tube.

A pressure blower provides circulation of the air, which is heated by elements in the duct downstream of the blower, its temperature being controlled by a bimetal type thermo-regulator and its flow by the orifice plates at blower inlet. Since the blower-heater section and the dust collection system are interchangeable, the drier can be arranged for either parallel or countercurrent flow.

Feed to the drier is by a manually controlled butterfly feeder, with motor drive if desired. Dried product is collected in a glass jar attached to the solids discharge port.

To ensure complete material balance as well as an accurate determination of dusting, an efficient cyclone dust collection system is included.

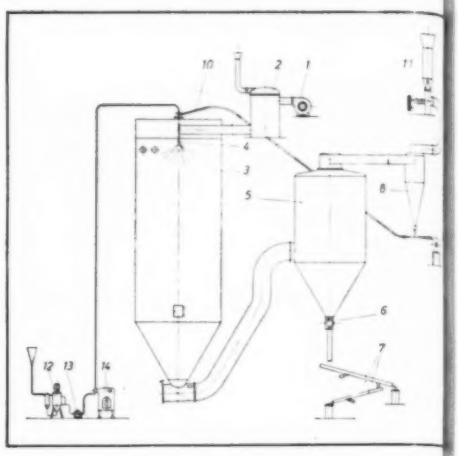
To give an idea of its performance, the following figures may be quoted for alum: at a feed rate of 4 lb/hr a product containing initially 20% moisture, wet basis, is dried to 0.82% wet basis, the air temperature being 319°F and the drier rpm 15. **The Bench Scale Equipment Co. Inc., Westfield, New Jersey.**

BCE 8970 for further information

Spray Drier

The special features of a recent continental spray drier construction include a settling box to which the spray-dried product is conveyed, the capacity of which can be controlled during operation. This allows the powder to be discharged continuously in a smaller range of particle sizes than is actually produced by the spraying unit. The separated particles are conveyed in the waste air to a group of cyclones, from where they are returned pneumatically to the drier. The collecting reservoir in the drier is so designed that the returned powder is easily absorbed by the sprayed wet product (see diagram).

For the counter-flow drying of detergents a modified design of spray drier is now being produced with direct discharge of the product at the drying tower, whereby a ring-channel construction for conveying the hot air to the drying tower avoids damage of the drying product by heat.



(1) *drying-air fan;* (2) *air heater;* (3) *drying tower;* (4) *atomising nozzle;* (5) *large separator;* (6) *rotary discharge valve;* (7) *screen and cooling channel;* (8) *centrifugal separator;* (9) *conveying air fan;* (10) *fine powder return;* (11) *extraction fan;* (12) *agitated container;* (13) *feed pump;* (14) *high-pressure pump.*

Industrie-Werke Karlsruhe Aktiengesellschaft, Karlsruhe, W. Germany.

BCE 8971 for further information

New Publications

Electric Counting and Batching Equipment

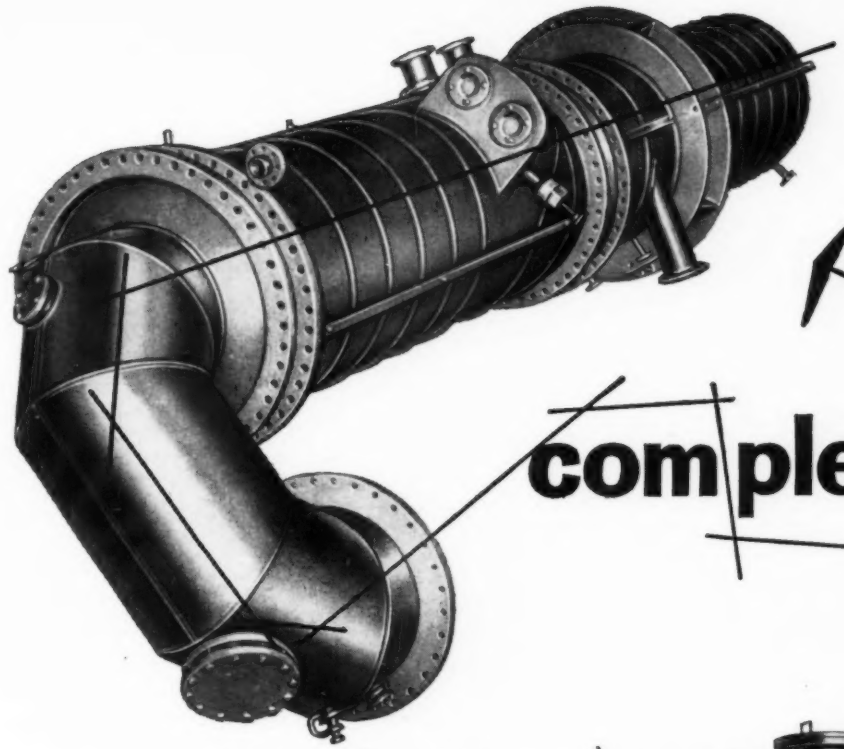
Two types of equipment are described in Data Sheet BC, Issue 1: a high-speed batch countertype, BC1, using Dekatron tubes in decade stages, and a simpler self-contained batch counting unit, type BC2, suitable for speeds of up to 600 counts per minute. The BC1 unit can be arranged to generate its own 100 c/s pulses, and can thus be used as a timer and as a time measurer, as well as a batch counter. The maximum counting rate is 500 counts per second, and the unit can either energise or deenergise a relay when the preset batch number is reached. The BC2 unit operates for a maximum count of 9999; the number is illuminated, and is visible through a window in the unit's cover. As counting proceeds, the counter displays a descending count, gives relay operation and resets to zero.—**Elcontrol Ltd., Wilbury Way, Hitchin, Herts.**

BCE 8972 for further information

Resins for Emulsion Polishes

In a 12-page booklet details and specifications are given of three resins: SR-83 (ammonia-soluble), SP-560 (terpene-phenol) and SP-561 (a blend of SP-560 and oleic acid). Descriptions are included of the preparation of ammonia-cut resin dispersions, wax-resin dispersions and wax-based emulsion polishes. A two-page section deals with formulation variations. **Schenectady-Midland Ltd., Oldbury, Birmingham.**

BCE 8973 for further information



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World of Chemical Engineering

Air Cooling in New Refinery

Esso's new oil refinery at Milford Haven is the first in the U.K. to be entirely cooled by air—not only a more economic method of cooling, but it also greatly reduces the risk of water pollution.

Another feature is the absence of the normal high visible flare. Instead, a new design ground flare will dispose of excess refinery gases where combustion is both highly efficient and invisible.

Construction of the refinery was started in July 1958 on a 350-acre site at the village of Herbrandston, about 2 miles west of Milford Haven town. It was completed in October 1960.

The refinery has been designed to process initially 4½ million tons of crude oil per annum with a staff of 330. The cost of construction was approximately £18 million.

There are four principal refining units: the primary crude oil distillation and light-ends recovery unit, which physically separates the principal ingredients of the crude oil; the Powerformer, which converts low octane naphtha from the distillation process into high octane motor spirit; the copper sweetening unit, which removes certain unwanted compounds from both petrol and jet fuel; and the Hydrofiner, which removes sulphur from gas and diesel oils.

There are 69 process and storage tanks with a total capacity of 189 million gallons and varying in size up to 54 ft high and 150 ft diameter.

All units are automatically controlled from one central control room. At a second control room the liquid level and temperature of every tank in the refinery are electronically recorded.

Urea and Fertiliser Factory in South Korea

Five West German firms are participating in the building of a urea and fertiliser factory in Naju (south-western part of South Korea). The factory will use as raw material the locally mined anthracite, will have a capacity of about 85,000 tons of urea annually, and is to go into production in 1961. The German firms Lurgi Gesellschaft fuer Waermetechnik m.b.H., Frankfurt, Linde Eismaschinen A.G., Munich, Friedrich Unde G.m.b.H., Dortmund (using the process of Inventa A.G., Chur, Switzerland), M.A.N., Nürnberg, and Siemens-Schuckert A.G., Erlangen, have prepared the plans for this new factory, are supplying plant and equipment, and are supervising the building and construction work, which is being carried out by local contractors of the South Korean Government. German technicians will also supervise the putting into operation of this plant. About 30 Korean engineers and chemists have spent half a year in the German factories which are participating in this project.

Petrochemical Industry on Swedish West Coast

Sweden's first petrochemical industry plant will be located at Stenungsund, on the west coast, north of Gothenburg. Negotiations carried on for some time have led to an agreement between Svenska Esso AB, which is to build a steam cracking plant, the forest industry group Mo och Domsjo AB, and Stockholm Superfosfat Fabriks AB, Sweden's largest electro-chemical industry, which is to form a joint company together with the American group Union Carbide Corporation for the purpose.

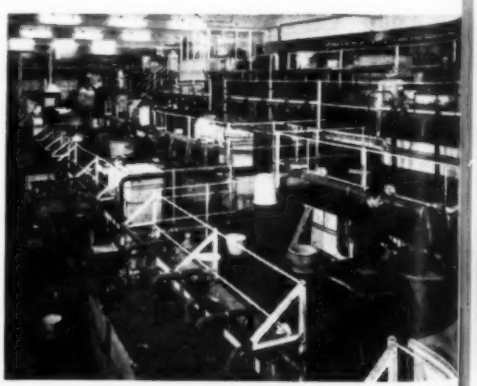
The aggregate investment of the three companies is estimated at close on Kr.200,000,000 (£13,800,000). Construction is to start on a major scale next spring and the plants are scheduled to go into operation in the summer of 1963. It is understood that other processing companies may later join the scheme, since the productive capacity of the cracker permits of such an expansion.

The steam cracker will produce ethylene, propylene and butadiene gases which will be supplied to the manufacturing plants by a tube system. The new subsidiary formed by Fosfatbolaget and Union Carbide will produce polythene plastics, which will be used, among other things, for the manufacture of foils for the packaging industry. The capacity will be about 15,000 tons per annum in the initial stage. Fosfatbolaget already has a sizeable output of PVC and melamine plastics.

Mo och Domsjo's plant at Stenungsund will have an initial capacity of some 10,000 tons of ethylene oxide a year. It constitutes the raw material for a number of products which, as hitherto, will be manufactured at the company's chemical plant at Ornskoldsvik, North Sweden. These products include an anti-freeze and compounds for the manufacture of synthetic detergents.

Platinum Refinery at Royston

A complex system of unplasticised PVC fume extraction pipework, fabricated and installed by Extrudex Ltd. at the new Royston platinum refinery of Johnson Matthey & Co. Ltd., has now been working satisfactorily for three years. The ductwork extracts from a succession of refining pans highly corrosive fumes which are carried away through PVC eliminator boxes and scrubbing towers, before release to the atmosphere. Previously, the only possible material for such an installation would have been stoneware or glass and the availability of PVC pipework enabled this precious-metal refining plant to dispense with the problems of handling these materials.



BCE 8916 for further information

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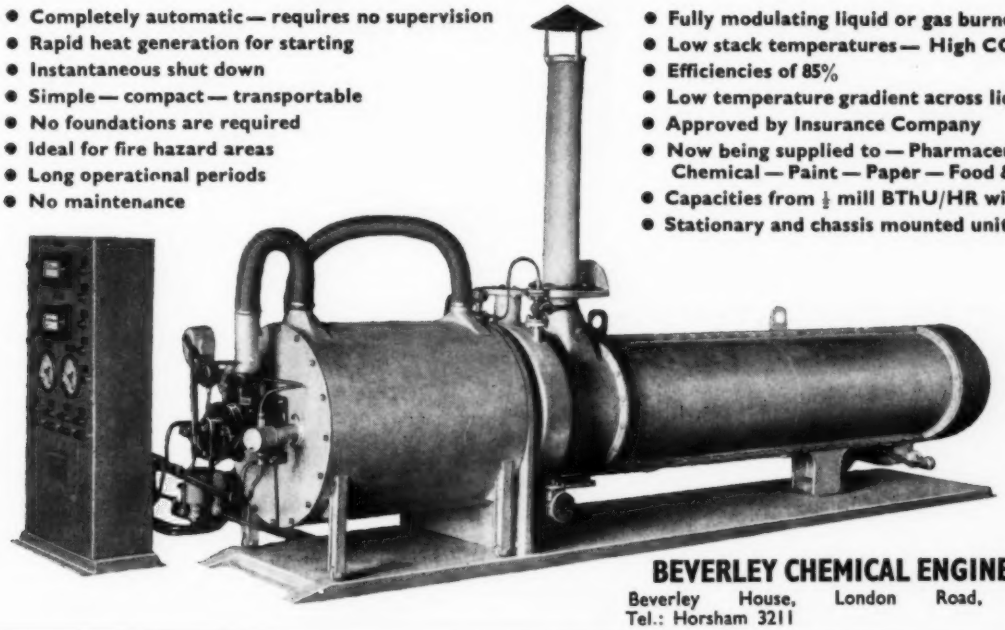

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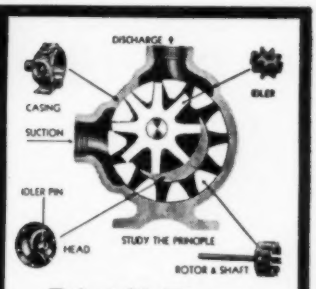

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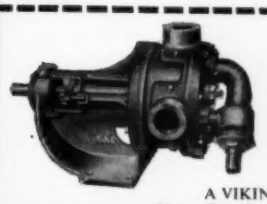
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BCE 8917 for further information

Benzole Hydrorefining Unit

The new benzole refinery of Port Talbot Chemical Co. Ltd. started in production ahead of schedule early in October. Initial production indicates that qualities of products are well up to those anticipated, and already a pure benzene of over 5.40 crystallising point has been obtained, with a sulphur content of below 5 p.p.m. Toluene, xylene and naphthas are all of similar low sulphur content, exceptionally colour stable, and highly aromatic. The crude benzole and coke oven gas (which provides the source of hydrogen) are derived from the coke ovens of the Steel Company of Wales Ltd., and the plant is the first of its kind in this country to produce pure benzene by hydrorefining.

The hydrorefining unit was designed by Lurgi and erected by Simon-Carves, while the distillation equipment has been supplied by R. & J. Dempster Ltd. in conjunction with Lurgi and Port Talbot Chemical Co. Ltd.

Water for Abu Dahbi

Pioneers of the vacuum flash evaporator in Britain, Richardsons Westgarth & Co. Ltd., have just dispatched to the Sheikdom of Abu Dahbi, on the Trucial coast, a plant believed to be the first of its kind.

This is a fully self-contained sea-water evaporator which will produce 14,400 gallons of drinking water a day. At the moment, the only supply of drinking water in Abu Dahbi is brought in by dhow at considerable expense.

Self-contained plants can be built of any size which can be handled as a unit to operate on any normal fuel.

In addition, the plant can be arranged, as this one is, to produce electric power to drive ancillary equipment such as fuel pumps, sea-water pumps, brine circulating pumps, etc.

Service for Exporters

To relieve the U.K. exporter of the legal, financial and shipping problems of supplying equipment abroad is the function of Conforex Ltd., a newly formed company. It has been formed to handle export problems such as consortium management, drafting of contracts, finance, E.C.G.D. cover, forwarding and shipping. Conforex aims primarily at providing management and exporting facilities for engineering consortia participating in large projects, but may also be of service to large and small companies. Full details from Conforex Ltd., 2 Princes Row, London, S.W.1.

QVF Form Canadian Company

Sales of British industrial glass in Canada have developed to such an extent that a Canadian subsidiary of the British industrial glass firm, QVF Ltd., has been formed in Ontario. It will be known as QVF Glass (Canada) Ltd. Distributors have been organised throughout the provinces of Canada and a very healthy stock position created in the Toronto area.

New Projects and Contracts in Brief

A polyurethane internal lining is to be used in two 30-in.-diameter steel water mains to be laid under the sea bed. They will carry filtered water a distance of 8 miles from Lantao Islands to Hong Kong Island as part of the Government's Skek Pik Water Scheme. Messrs. Spencer & Partners, specialists on corrosion problems, have advised the consulting engineers, Messrs. Binney, Deacon & Gourley, to use a Prodor-film lining to be supplied by Prodorite Ltd. This film is built up of a series of multi-layers which are spray-applied to the shot-blasted pipe. It cures at room temperature to give a hard, completely non-tainting, chemical-resistant lining, equal to the best obtained with high-temperature stoved linings. The surface area to be covered is approx. 700,000 sq. ft.

Two of Britain's largest companies—I.C.I. Ltd. and the British Petroleum Co. Ltd.—are to build large plants in Northern Ireland in the near future.

I.C.I. have bought a 200-acre site at Kilroot, near Carrackfergus, Co. Antrim, for a factory for the production of terylene and possibly other man-made fibres, and B.P. intend to build an £8 million oil refinery at Sydenham, between Belfast and Holywood, Co. Down.

I.C.I. will start building at Kilroot early next year, with a view to going into production in 1963, and work on the B.P. refinery, expected to be completed in two years, will also commence in 1961. The refinery will have a capacity of 1.3 million tons of crude oil a year and will produce petrol, kerosene, aviation turbine fuels, light and heavy diesel oils, fuel oil and liquefied petroleum gas.

A complete gas cleaning plant is to be supplied by Chemical Construction (G.B.) Ltd. to Gutehoffnungshutte (GHH), to be used in conjunction with the oxygen steel-making rotor furnace GHH are supplying to Richard Thomas & Baldwins at their Redbourne works in Scunthorpe, Lincs. This project will be the first application of the Chemico P-A venturi scrubber in the United Kingdom for the elimination of iron oxide fumes from an oxygen steel-making plant.

The gas cleaning plant will handle 106,000 cfm of saturated gas and includes a filtration plant for the removal of solids from the scrubbing water. It is expected the installation will be in operation early in 1961.

The Kestner Evaporator & Engineering Co. Ltd., London, have recently received an order for two evaporators for concentrating an acid electrolyte liquor. These evaporators will form part of a complete installation for the continuous production of tinned steel strip, ordered from and engineered by The Head Wrightson Machine Co. Ltd. The evaporators are of the single-effect climbing-film type, working under vacuum and are of Monel metal construction. The plant will be installed at the Ebbw Vale works of Richard Thomas & Baldwins Ltd., and is due for starting up during 1961.

Forth Chemicals Ltd. are to build a new 50,000 tons p.a. styrene monomer plant between Neath and Port Talbot, South Wales, at a cost of more than £3 million.

The new plant will be located next to the site selected by British Hydrocarbon Chemicals Ltd. for its own recently announced expansion plans, near B.P.'s Llandarcy refinery. Design and engineering of the new Forth plant will be carried out by Monsanto Chemicals Ltd., and the plant is expected to take approximately two years to come into operation.

Forth is the largest British manufacturer of styrene monomer. Its Grangemouth plant, built in 1953, has been twice expanded, and a third expansion currently approaching completion will bring total production there to 50,000 tons a year. The completion of the new Welsh plant will consequently bring Forth's total production to 100,000 tons a year.

Ethylene for the new plant will be provided by British Hydrocarbon Chemicals and benzene will be purchased from outside sources.

Marchon Products Ltd. announce the construction of a plant to manufacture sulphamic acid (amido sulphonic acid) with a capacity more than sufficient to meet the whole of the United Kingdom's known requirements. The plant will be at the company's Whitehaven factory. The manufacture of ammonium sulphamate is also contemplated. Sales of both materials will be in the hands of Albright & Wilson (Mfg.) Ltd.

A sea water distillation plant capable of producing 120,000 gallons of fresh water daily has been ordered from G. & J. Weir Ltd, of Glasgow. The plant is to be installed at Luderitz, South West Africa, and will be similar to the one recently installed in Guernsey. The installation will operate in conjunction with an existing electricity generating station, and will use bled steam from the main turbines as the heating medium.

A new chemical plant, to be known as the manufacturing unit of Nalco de Mexico, S.A., de C.V., is to be built at Saltillo, Mexico. It will house equipment to manufacture liquid, pellet and pulverised chemicals and should be completed by February 1961. The parent company is Nalco Chemical Co., of Chicago, Illinois.

Union Carbide do Brazil S.A. are to increase the capacity of their polyethylene plant, located near Santos, Brazil, from 9 million lb/yr to 24 million lb/yr. Design and engineering work for the plant extension have been completed and construction will start immediately.

Chemical Construction (G.B.) Ltd. is to supply a P-A venturi and cyclonic gas scrubber to Glass Bulbs Ltd. It will handle approximately 6000 cfm of saturated gas containing hydrofluoric acid fume. The installation will be at their Harworth works near Doncaster.